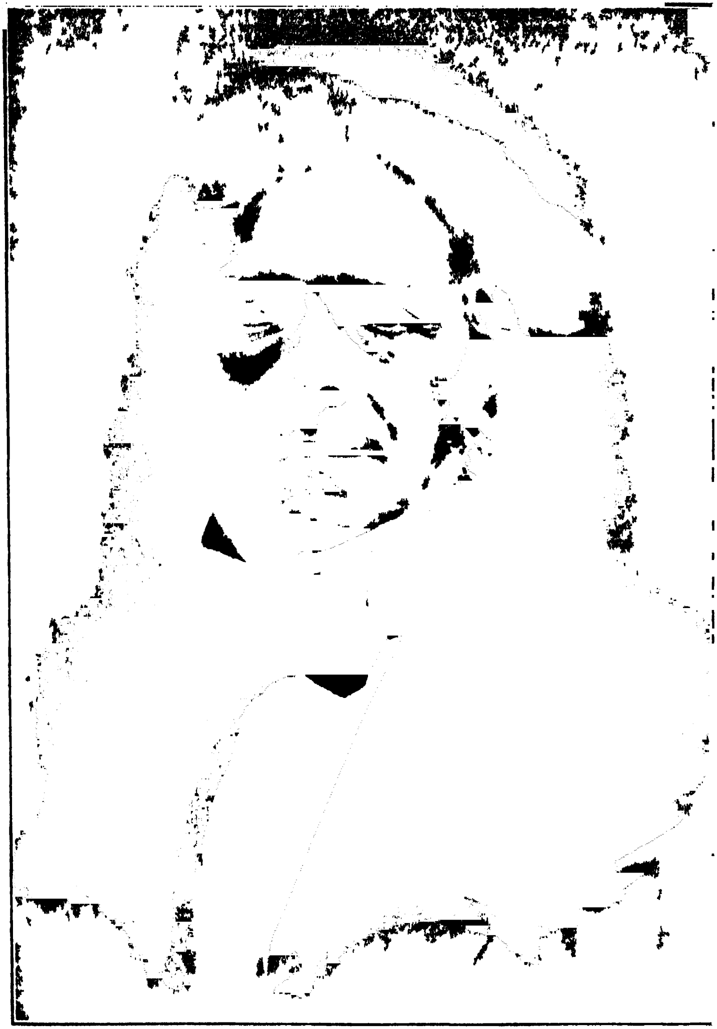


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PHOTOGRAPH OF MICHAEL FARADAY

TRANSMITTED OVER A TELEPHONE LINE

(See page 627)

SWOOPE'S
LESSONS IN
PRACTICAL ELECTRICITY

AN ELEMENTARY TEXT BOOK

SEVENTEENTH EDITION

REWRITTEN, REVISED AND ENLARGED

BY

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PREFACE

THE original edition of this book was written by Mr. C. Walton Swoope in 1900 primarily for the use of students in practical electricity at the Spring Garden Institute in Philadelphia. The instruction was given in the evening to large classes of young men who were engaged in various occupations during the day and who desired a working knowledge of the principles and arithmetic of applied electricity. It was deemed best to divide the instruction between the lecture room and the laboratory, and accordingly the book was prepared to combine statements of the principles of electricity, instructions for the experimental demonstration of these principles, descriptions of electrical apparatus and devices, and practical methods used in calculating and measuring electrical quantities. This policy was continued in revisions made after the author's death in October 1901 by his former student, assistant and successor at the Spring Garden Institute, Mr. Harry N. Stillman.

The success of the book in presenting the subject of electricity to the beginner in a manner that is both easily understood and sufficiently complete, is evidenced by the satisfaction it has given to teachers and by the achievements of their former students. It has also been found particularly suited to those who desire to study for themselves the fundamentals of practical electricity. The many editions of the book and its wide use by schools and by individuals is material proof of its merit.

In the complete revision of the book commenced shortly before Mr. Stillman's death in May 1920, he and the writer modified many of the lessons in keeping with the advances made in electrical engineering, and also added three lessons, namely: Alternating-current Apparatus and Machinery, Alternating-current Motors, and Radio Signaling. The present revision has again brought the text up-to-date, and also three lessons have been added.

Particular attention has been directed to improvements in the presentation of the subject of alternating currents; two lessons

covering twice as much space as formerly are now devoted to this subject. The lessons on Primary Cells, Electric Lighting, and Electromagnetic Induction have been thoroughly overhauled. The new lessons are devoted to Vacuum Tubes and to Telegraphy and Telephony, and the treatment of radio signaling has been expanded into two lessons; these changes having been made to meet the present widespread interest in all phases of electrical communication.

Thanks are extended to the various electrical manufacturing companies for supplying illustrations and cuts of the apparatus and machinery herein shown.

E. Hausmann

Polytechnic Institute of Brooklyn
October 1, 1926

CONTENTS

In the manufacture of this book, the publishers have observed the recommendations of the War Production Board and any variation from previous printings of the same book is the result of this effort to conserve paper and other critical materials as an aid to the war effort

LESSONS IN PRACTICAL ELECTRICITY

LESSON I

MAGNETS

Magnets — The Poles — Magnetic Attraction and Repulsion — Magnetic Substances — Making Permanent Steel Magnets — Magnetization — Laminated Magnets — Horseshoe Magnets — Practical Application of Permanent Magnets — The Earth as a Magnet — The Earth's Magnetism Used in Navigation — The Mariner's Compass — Questions.

1. Magnets. — The name *magnet* was first applied by the ancients to lead-colored stones, known as oxide of iron, magnetite, Fe_3O_4, because they possessed the power of attracting small particles of iron or steel. Later, the Chinese discovered that if a piece of the ore was freely suspended, it would assume a position pointing north and south, hence, they gave it the name of lodestone (meaning leading stone).

If the lodestone is dipped into iron filings, it will be found that the attraction for the filings seems to be centered at two or more points on the stone, while at other points no filings are attracted. This property of attracting iron and steel is called *magnetism*, and a body possessing it is called a *magnet.* The lodestone is called a *natural* magnet, since it possesses magnetism when taken from the earth.

The natural magnet possesses a third important property, namely, that of imparting all of its properties to a small piece of hard iron or steel when they are rubbed together. Besides the natural magnet, magnets are classified into *artificial, permanent,* and *temporary magnets.* A piece of steel rubbed with lodestone, or magnetized in any other way, becomes an *artificial*

magnet, and if the steel retains its magnetism indefinitely, it would be termed a *permanent* magnet. A *temporary* magnet is any magnetizable substance that possesses the property of attracting filings while under the influence of another magnet. Figs. 1 and 2 illustrate a natural and an artificial magnet respectively. *A magnet would be defined as a piece of steel, or other magnetized substance, which possesses the properties of attracting other pieces of steel or iron, or magnetizable bodies to it, and of pointing, when freely suspended in a horizontal position, toward the north pole of the earth.*



Fig 1 — Natural Magnet Attracting Iron Filings

2. The Poles. — In observing Fig. 2 it will be noted that the attraction of the magnet for the filings is greatest at both ends of the magnet, and that there is practically no attraction at the center. The ends of a magnet, where the attraction is strongest, are termed its *poles*. The end which points toward the north geographical pole is generally called the North pole, and is usually marked on that end of the magnet by an **N**, or a line cut in the steel, while the other, unmarked, end is the South pole. By the term *polarity* we mean the nature of the magnetism at a particular point; that is, whether it is north- or south-seeking magnetism.

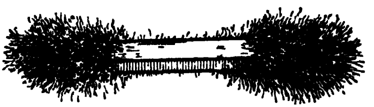


Fig 2. — Magnetized Steel Bar Attracting Iron Filings.

3. Magnetic Attraction and Repulsion. — If a thin piece of magnetized steel in the form of an elongated lozenge be pivoted so that it is free to move, it will assume a definite direction pointing *north* and *south*. When a magnet is thus mounted, it is termed a *horizontal magnetic needle* (Fig. 3). A small magnetic needle, poised on a jewel bearing above a graduated scale, fastened to, or engraved on a containing box,

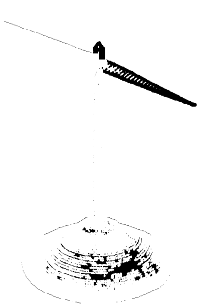


Fig 3 — Horizontal Magnetic Needle.

having a glass cover, is termed a compass (Fig. 4). Either the compass or horizontal needle may be used for determining the polarity of magnets and for studying magnetic attraction and repulsion.

Experiment 1. — With the magnetic needle or compass referred to above, and a bar magnet held in the hand, bring the **N**-pole of the magnet to the **N**-pole of the needle (Fig. 5); *repulsion* of the **N**-end of the magnetic needle occurs. The same effect will be noted if two South poles are brought near each other. If, however, the **S**-pole of the magnet is brought near the **N**-pole of the needle (Fig. 6), *attraction* of the magnetic needle occurs.

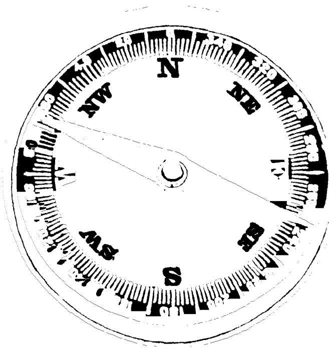


Fig. 4. — Magnetic Compass.

Like poles repel each other, and unlike poles attract each other.

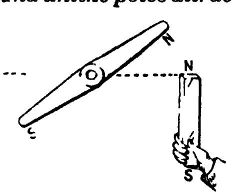


Fig. 5. — **N**-Pole Repels Another **N**-Pole.

The above experiment can be made with a piece of lodestone and the location and polarity of the several poles in the lodestone determined.

4. Magnetic Substances. — There is a distinction between magnets and magnetic substances. A magnet attracts only at its poles. A piece of iron will attract a magnet, no matter what part of it approaches the magnet; it does not possess fixed poles or a neutral point, while a magnet has at least two poles, one of which always repels one pole of another magnet.

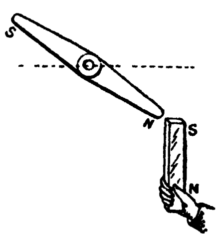


Fig. 6. — **S**-Pole Attracts a **N**-Pole.

The *magnetic metals* used in practice are *steel* and *iron*. Besides these, the metals nickel, cobalt, chromium, and cerium are attracted by a magnet, but only very feebly. Nickel and cobalt are the best of this class, but are very inferior to iron or steel. For practical purposes all other substances, such as copper, lead, gold, platinum, wood. rubber.

glass, etc., may be regarded as unmagnetizable, or nonmagnetic substances. Magnetic attraction or repulsion will, however, take place through these substances.

5. Making Permanent Steel Magnets. — Some varieties of steel which possess good machine-tool properties are not adapted to making good permanent magnets. Steel containing a certain percentage of manganese cannot be magnetized, while some brands of cast steel, spring steel, and mild plate steel are readily magnetized, but do not retain their magnetism permanently. The best permanent magnets are made from a special brand of steel known as *magnet steel*. If the special magnet steel cannot be obtained, a piece of good, close-grained, rolled steel that has not been heated since it was made will do; the steel should be "glass hard," that is, tempered by being heated to a red heat and suddenly immersed in water or oil. It will become very brittle and can be magnetized by any of the methods hereafter given.

6. Magnetization. — A bar of steel, after being tempered, may be magnetized by either of the methods illustrated in Figs. 7 and 8, where use is made of another strong permanent magnet.

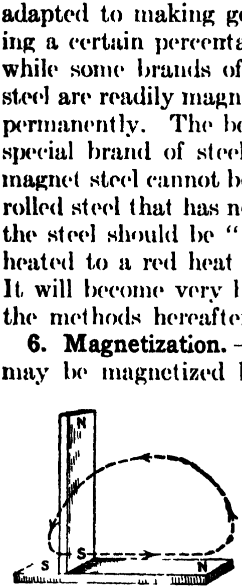


Fig. 7. — Magnetizing a Steel Bar with a Permanent Magnet (Single-stroke Method).

The bar to be magnetized is laid on a table and, beginning at the unmarked end of the steel bar, stroke its entire length with the South end of the strong permanent magnet. Lift the magnet clear at the end and return again for a second stroke in the direction of the dotted line and arrows in Fig. 7. Stroke all sides of the bar you are magnetizing about ten times in this manner. This is known as the single-stroke method. After magnetizing the bar of steel, it may be tested by suspending it, noting if the marked end points toward the north when it comes to rest. Note that the **N**-pole in the magnet you have made was always touched last by the **S**-pole of the magnetizing magnet. One pole always induces the opposite pole in any magnetizable body at the point where the pole last leaves that body, ¶ 21.

A stronger magnet will be obtained by magnetizing each

half separately, as illustrated in Fig. 8. Stroke one half of the steel bar with the **S**-pole, beginning at the center and following the direction of the dotted lines. Repeat this a number of times on each side; then, using the **N**-pole, stroke the other half in the same way.

A still better method of magnetization is by means of an electric current. If a number of turns of insulated wire be

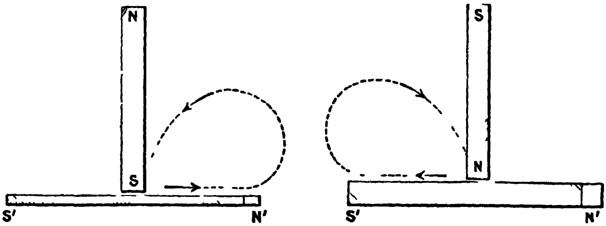


Fig 8 — Magnetizing Each Half Separately.

wrapped around the steel bar (Fig. 9) to be magnetized, and a strong current of electricity passed through the coil from a battery or an electric generator, the steel will be found permanently magnetized with a **N**-pole and a **S**-pole after the current is turned off. Instead of winding the wire around the bar, the bar can be inserted in a spool containing many turns of insulated wire, through which the electric current is passed.

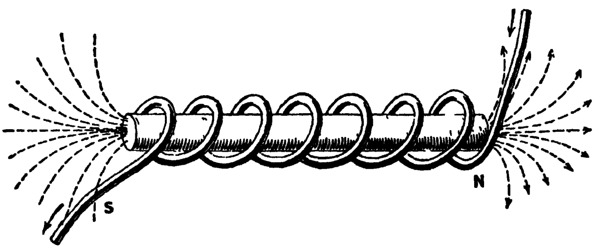


Fig. 9. — Magnetization by an Electric Current.

7. Laminated Magnets. — If a thick piece of steel be magnetized and then placed in an acid bath (such as nitric acid) for some time, whereby the outer surface is eaten off, and then tested for magnetic qualities, it will be found to be almost

entirely demagnetized. From this experiment it is inferred that the magnetism has only penetrated the surface of the steel. If a permanent magnet then be made up of a number of thin pieces of steel, magnetized separately, and fastened together with like poles at the same end, it will be stronger than one of solid steel of the same dimensions, because it is more thoroughly magnetized. Such magnets can be made in any form and are known as *laminated* magnets; a horseshoe laminated magnet is shown in Fig. 10.

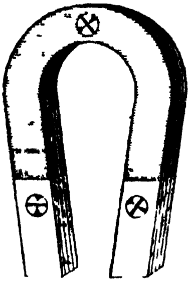


Fig. 10 -- Laminated Horseshoe Magnet.

8. Horseshoe Magnets. — When a straight bar of steel is bent into the form of a horseshoe, and then properly magnetized, the end of one limb will be a N-pole and the other a S-pole. By bringing the poles close together in this manner the magnet will exert a force much greater than the sum of the attractive forces when used separately; because in a bar magnet only one pole could be used at a time, while now both poles act together. A piece of soft iron, called the *keeper*, is placed across the ends of the poles when they are not in use, to assist in preventing the loss of magnetism. Fig. 11 illustrates a horseshoe magnet of rectangular cross section, with its keeper, K, attached. Fig. 12 illustrates the proper method of putting away two bar magnets with their keepers, to prevent loss of magnetism; the unlike poles are placed at the same end, with the keeper connecting them.

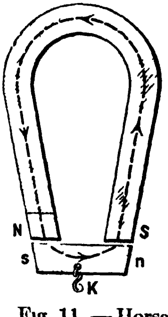


Fig 11. — Horseshoe Magnet and Keeper.

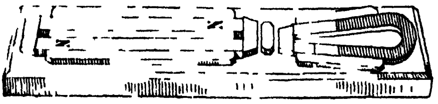


Fig. 12. — Student's Magnet Set.

9. Practical Application of Permanent Magnets. — Permanent magnets are used extensively in electrical measuring

instruments. Fig. 13 illustrates a powerful horseshoe magnet used by the Weston Electrical Instrument Company for their portable ammeters and voltmeters for direct-current work. Fig. 14 illustrates the form of permanent magnet used to produce a load or drag on the copper disk in the Thomson watt-hour meter.

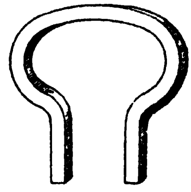


Fig. 13. — Horseshoe Magnet Used in the Weston Electrical Measuring Instruments.

Permanent magnets may also be found in nearly all telephone receivers and magneto-electric generators. It is quite important that magnets used for these purposes should not change appreciably in magnetic strength with time. In order that such magnets will not suffer any appreciable loss of their high magnetic strength when used, they are put through a process of *aging*. They are subjected to certain temperature changes and vibrations, which have the effect of settling their strength at a value that is nearly permanent.

Permanent magnets, or instruments containing them, should be handled with great care, as heat and rough treatment will soon weaken them.

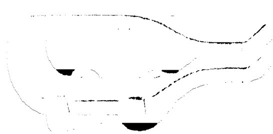


Fig. 14. — Form of Horseshoe Magnet Used in the Thomson Watt-hour Meter.

10. The Earth as a Magnet. — Experiment 1 would indicate two kinds of magnetism, or two kinds of magnetic poles, which attract or repel each other, one pole tending to move toward the geographical north pole, and the other pole toward the geographical south pole. Since we have called the north-pointing, or marked pole, the **N**-pole, then the magnetism of the earth near the north geographical pole must be of the opposite kind, or south magnetism, since unlike poles attract each other. A compass needle assumes the position pointing north and south, because the earth possesses the property of a magnet, having a *magnetic North* and *South pole*.

The true **S** magnetic pole is located in the northern hemisphere, while the true **N** magnetic pole is in the southern hemisphere (Fig. 15). The earth's true magnetic **S**-pole is

not coincident with its north geographical pole, but about 1400 miles away from it. A compass needle points its north-seeking pole in the direction of the S magnetic pole; this deviation of the needle's N-pole from the geographical north pole in general becomes more marked as the compass needle is carried farther north on the earth. This deviation of the needle is known as the *angle of declination* of any given place, and indicates just how far away from the true geographical north the compass needle points.

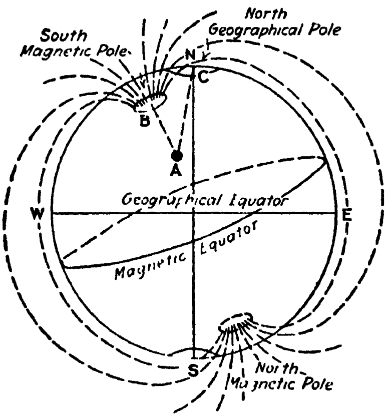


Fig. 15. — The Earth's Magnetic Poles and Equator.

If a steel knitting needle be carefully balanced and suspended by a silk thread, it will assume a horizontal position. When it is magnetized, its N-end will point downward in the northern hemisphere or dip toward the earth's magnetic S-pole. This needle, being free to move in all directions, assumes a position pointing in the direction of the earth's magnetic force. The angle which the needle makes with the horizontal is termed the *angle of dip*. The *dip needle* is horizontal at the magnetic equator, the angle of dip increasing as you go toward either magnetic pole.

An imaginary line encircling the earth midway between its magnetic poles and connecting all those points which show no magnetic dip, or where the dip needle was found to be horizontal, is called the *magnetic equator*, just as the geographical equator is an imaginary belt passing around the earth midway between its poles (Fig. 15). The magnetic equator is somewhat irregular in form, owing to the irregular distribution of the earth's magnetism.

11. The Earth's Magnetism Used in Navigation. — In ¶ 10 the angle of declination at any given place is defined as the

deviation of the magnetic needle from the true north; it may also be defined as the angle between the *magnetic meridian* and

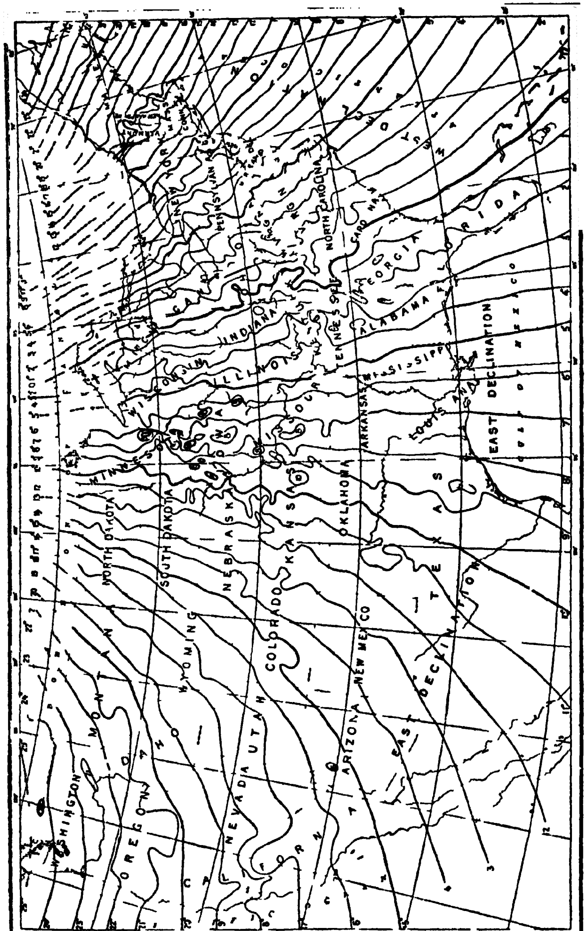


Fig 16 — Magnetic Map of the United States
Isogonic lines join places having the same declination

the geographical meridian, since the magnetic meridian at a location is the direction of a magnetic needle at that location,

as the line AB (Fig. 15). The magnetic meridian may be regarded as an imaginary line drawn on the earth in a plane which passes through the magnetic poles of the earth and a given place. The geographical meridian is an imaginary line drawn on the earth's surface in a plane which passes through the geographical poles and a given place, as line AC (Fig. 15). The angle between lines AB and AC is known as the angle of declination at point A.

The angle of declination varies at different locations on the earth's surface and is slowly but constantly changing. In Columbus, Ohio, and Charleston, South Carolina, in 1900, the declination was zero; that is, the geographic pole was just in line with the magnetic pole at these points, or the two meridians coincided. Moving west from point A (Fig. 15), the declination decreases until a locality is found in Central Asia where the meridians again coincide. Places in the Atlantic Ocean, Europe, and Africa, between these lines of no declination, would have a declination west of the true north, while at places on the other side of the globe between these lines the needle would point east of the true north.

In steering ships at sea by the compass, references are made to a chart, giving the values of the declination of the magnetic needle at different localities on the earth's surface. The charts, or magnetic maps, are prepared by the United States Geodetic Survey and, in addition to giving the angle of declination at different localities, it contains lines connecting places of equal magnetic declination, called *isogonic lines* (Fig. 16).

12. The Mariner's Compass. — The small pocket compass (Fig. 4) is merely a nicely balanced and pivoted magnet, contained in a brass case to exclude disturbing draughts of air, and provided with a suitable scale indicating north, south, and intermediate points. In using this compass to determine direction, it is first necessary to permit the needle to come to rest so as to point north and south, and then gently twist the box around until the point marked **N** on the scale is directly under the **N**-pole of the needle. The true geographical north will then be so many degrees east or west of the position assumed by the **N**-pole of the needle on the scale, depending on the amount of declination.

The *mariner's magnetic compass*, which is quite sensitive and arranged for nautical observations, may be either of the "dry-card" type or of the "liquid" type. In the dry-card type the magnetic needle is fastened to the under side of a cardboard scale, which is pivoted inside the compass bowl. The scale is divided into the thirty-two "points of the compass" (Fig. 17), and swings with the magnetic needle; the **N**-point on the scale always points to the north. When it is desired to steer in any particular direction, as northwest, the ship's helm is turned till the point **NW** on the movable scale is opposite a fixed vertical black line (termed the "lubber's line"), which is drawn on the inside of the compass bowl, in line with the direction of the ship's motion. The compass box is supported on gimbal bearings, so that no matter how much the ship may roll or lurch the card will always be level.

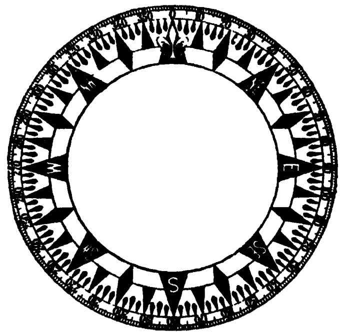


Fig. 17. — Scale of the Mariner's Compass.

The magnetic compasses of the liquid type were first developed in this country, and after many years of trial have been found to be better adapted for naval use than the dry-card compass, and are now generally used throughout the world on naval vessels. The advantage of their use is the greater steadiness of the card when subjected to the shock of gun-fire and the greater steadiness in a rough sea. The liquid compass allows the use of more powerful magnets, and therefore has greater directive force and sensibility.

The construction of a standard liquid compass used in the Navy is shown in Fig. 18. In the center of the card P is located a spheroidal air-vessel Q to buoy the card and magnets, which are immersed in the liquid (45 per cent alcohol and 55 per cent distilled water) which entirely fills the bowl, D. The magnets O consist of four cylindrical bundles of highly magnetized steel wires contained in sealed cylindrical cases, the magnets

being placed parallel to the north and south line of the card. The cast bronze bowl is weighted with lead J at the bottom. A pivot M is fastened to the bottom of the chamber, which supports and also keeps the card P in its position. Beneath the bowl is a self-adjusting expansion chamber K, of elastic metal, having two small holes, L, to permit circulation of the liquid between the bowl and expansion chamber, thus keeping the bowl free from bubbles. Two lubber's lines are drawn on enameled plates inside the bowl. The bowl is supported in gimbal bearings; B is one gimbal ring and A is one of its knife edges which rests on the other gimbal ring. The bowl

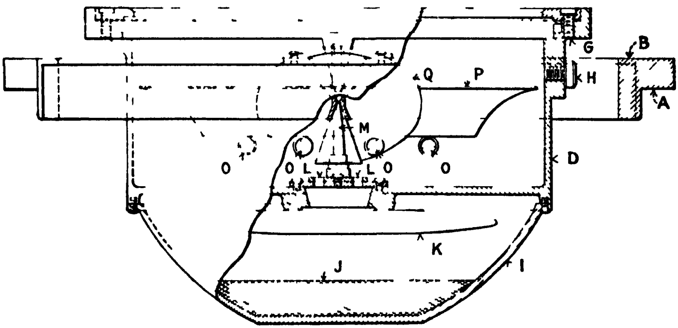


Fig. 18.--Sectional View of the Liquid Type of Magnetic Compass.

and compass card are accurately balanced with lead weights. The scale for this compass is the same as shown in Fig. 17.

Mariner's magnetic compasses require frequent adjusting in order to insure accuracy, and many precautions have to be taken in adjusting a ship's compass to compensate for errors likely to arise, due to the influence on the magnetic needle of the hull, of the cargo, or of electric light wires in the vicinity, etc.

A compass that is not dependent upon the earth's magnetic force for the movement of the " card " is the " gyro-compass." Gyro-compasses are now being installed by the Navy Department on all new battleships and submarines. The difficulty in properly compensating magnetic compasses on such vessels, for various magnetic latitudes, has increased greatly

with the increase in size of the vessels, and with the use of great masses of moving steel in the turrets and guns. The gyro-compass, being subject to no magnetic influence whatever, has solved the problem of obtaining an efficient battle compass, and experience has demonstrated that it is also to be used for navigation purposes practically at all times. The magnetic compass, however, will always be retained for a check on the gyro-compass, and for use in case of casualty to the latter. The advantages of the gyro-compass over the magnetic compass are: it is not subject to magnetic influence, or to sudden changes in magnetic condition, resulting from the training of turrets and boat cranes, operation of electric generators or motors, etc.; it always points true north, thereby eliminating magnetic declination and its variations; it maintains a steady heading while rolling, and is sensitive only to actual changes in course.

The operation of the gyro-compass is based on the principle of the gyroscope, which consists essentially of a heavy rotating wheel, the axis of which is free to turn in any direction. When the wheel is revolving at high speed its axis assumes a position parallel to the axis of the earth. For a description of the construction and operation of the gyro-compass, the student is referred to "Practical Manual of the Compass," published by the Naval Institute, Annapolis, Maryland.

QUESTIONS

1. What is a natural magnet?
2. What three important properties does it possess?
3. How would you locate the poles on a natural magnet?
4. Distinguish between a natural and an artificial magnet.
5. You are given two similar bars of steel, only one of which is magnetized. What tests would you apply to determine which one is magnetized?
6. Define a magnet.
7. State the law regarding magnetic attractions and repulsions.
8. What is the difference between a magnet and a magnetic substance?
9. What do you mean by *polarity?*
10. A bar magnet is floated on a cork; the N-end is toward the observer. What occurs when a S-pole is approached to the S-end of the floating magnet? What effect when the N-end is approached to this same end?

11. What is the difference between a permanent and a temporary magnet? Give an example of each class.

12. You are given a hard steel bar with a notch filed at one end. How would you magnetize it by using the N-pole of a magnet so that the notched end would have a N-pole?

13. What two tests would you apply to prove that although a piece of iron attracts the N-pole of a suspended bar magnet yet it is not itself a magnet?

14. Give a general classification of magnets, citing an example to illustrate each class.

15. How would you magnetize a steel sewing needle by the method of magnetizing each half separately, so that the eye would be a N-pole? Give a sketch.

16. What kind of steel would you select to make a good permanent magnet?

17. What is a laminated magnet? How would you put four horseshoe magnets together to make a laminated magnet?

18. What is the advantage of laminated magnets over those made from solid steel?

19. Describe the liquid type of magnetic compass.

20. What are isogonic lines?

LESSON II

MAGNETISM

The Nature of Magnetism — Proof of the Molecular Theory of Magnetism — Magnetic Saturation — The Magnetic Difference between Iron and Steel — Magnetic Force — The Magnetic Field — Axis and Equator of Bar Magnet — Magnetic Bodies Free to Move — Magnetic Induction — Magnetic Screens — Consequent Poles — Pole Pieces and Armatures — Questions.

13. The Nature of Magnetism. — The so-called *molecular theory of magnetism* is offered as an explanation of the phe-

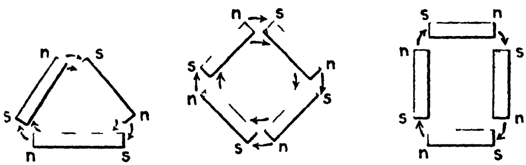


Fig 19 — Possible Arrangement of Molecular Magnets in Unmagnetized Bar (Magnified).

nomena arising from the magnetism of a piece of steel or iron. The theory assumes that a bar of steel or iron, composed like all matter of small molecules, is made up of minute magnets. If the steel or iron is not magnetized, these molecules arrange themselves promiscuously in the body; but according to the law of attraction and repulsion between unlike poles, the magnetic circuits are satisfied internally, and there is no resulting external magnetism. Fig. 19 illustrates several possible geometric figures which the molecules may assume in an unmagnetized bar of steel or

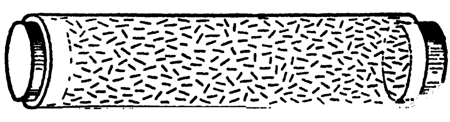


Fig. 20. — Glass Tube of Steel Filings before Magnetization.

iron. When the bar is magnetized, the molecules rearrange themselves according to the law of attraction, turn on their axes, and assume positions more nearly in a straight line, with their **N**-ends pointing the same way. The closed magnetic circuits are thus broken up, and external magnetism made evident.

14. Proof of the Molecular Theory of Magnetism. —

Experiment 2. — Fill a small glass tube with coarse steel filings, and insert a cork at each end. Test each end of the tube for magnetism by bringing it near a suspended needle. Either end attracts the same pole of the needle, proving that it is not magnetized, Fig. 20. To prove that a body is a magnet there must be repulsion between the body and magnetic needle. Magnetize the tube of filings by any of the methods previously given, being careful not to shake it. Test again with the needle; one end repels one pole of the needle and attracts the other pole. The filings are now located somewhat as shown in Fig. 21.

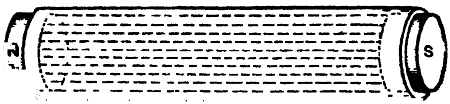


Fig. 21. — Glass Tube of Steel Filings after Magnetization.

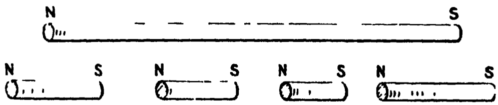


Fig. 22. — Breaking a Steel Magnet.

Now shake the tube thoroughly so as to intermingle the filings; repeat the tests above, and you find that the tube is no longer a magnet, but has been demagnetized.

Experiment 3. — Magnetize a long, thin piece of tempered steel and mark the **N**-pole. Break it in half and test each piece separately. In one half the **N**-pole remains **N**, as previously marked, but a new **S**-pole is developed, while in the other piece the **S**-pole remains as before and a new **N**-pole is developed. Break these pieces again (Fig. 22), and each part is a perfect magnet, with the poles distributed as in the previous case. Break the remaining pieces until they become too small to be broken further. Upon test, each piece will still be found to be a magnet.



Fig. 23. — Magnified Arrangement of Particles in a Bar Magnet.

From the above experiments we would infer that a steel or iron magnet is an aggregation of small magnets, arranged as shown in the magnified view given in Fig. 23.

15. Magnetic Saturation. — We cannot see the molecules of iron or steel changing their relative positions under the influence of magnetism, but these experiments are intended to show what probably takes place when steel or iron is magnetized. According to the theory, the unmagnetized iron or steel has its molecules irregularly disposed, as were the steel filings in the tube when shaken. Magnetization turns them around on their axes until they are arranged symmetrically. When they have all been turned around the bar is said to be saturated, or completely magnetized; it cannot be further influenced by magnetism, however strong the force.

16. The Magnetic Difference between Iron and Steel. —

Experiment 4. — Insert a bar of steel in a coil carrying a current of electricity; test its attractive power by nails or filings while the current is on. Then insert a bar of soft iron of the same size in the coil; test its attractive power while the current is on. Now test the attractive power of both with the current off.

The soft iron will be found to possess greater attractive force than the steel, when the current is on, while the steel possesses far superior attractive properties to the iron, after the current is turned off. The iron is magnetized very slightly. The magnetism remaining in the iron is known as *residual magnetism,* and is a most important factor in operating generators since upon it their self-exciting properties depend. The power to retain magnetism is called *retentivity.* In a steel magnet the molecules tend to retain the magnetic position, shown in Fig. 21, hence they possess permanent magnetism. On the other hand, nearly all the molecules of soft iron tend to return to their original position (Fig. 20) when the magnetizing force is removed. The greater the retentivity of a magnetizable body, the more force must be applied to magnetize it. The retentivity of steel is much greater than of iron, due to the fact that intermolecular friction is greater than in iron.

17. Magnetic Force. — The force exerted by one magnet on another, to attract or repel it, or to attract iron filings, is termed *magnetic force.* It is not perceptible to any of the senses, but its effects will reveal its existence. When the magnet is plunged into filings, the attraction for them exhibits the magnetic force, its direction, and its distribution in the space

surrounding the magnet. The magnetic force is not the same at all distances, but decreases as the distance from the magnet increases.

The magnetic force acts in all directions from a magnet. To ascertain the direction of the force in the space surrounding a magnet, a small dip needle may be used, as shown in Fig. 24.

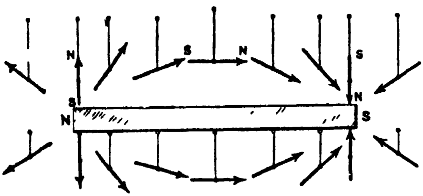


Fig. 24. — Exploring the Magnetic Field about a Bar Magnet.

With the bar magnet flat on the table, place the dip needle a short distance above the magnet midway between its poles. The needle takes up a position parallel to the magnet, with its **N** and **S** poles attracted by the unlike poles of the magnet. By moving the needle toward either pole, the needle will incline toward the magnet, the angle of inclination increasing as you approach the pole, until it becomes vertical at the pole. If the magnet is laid on a sheet of paper, and the dip needle is used to explore its magnetic force by moving the needle slowly from one end of the magnet to the other on both sides, the direction that the needle points can be recorded for each position. The direction of the magnetic force around the magnet will then be approximately as is illustrated in Fig. 25, wherein the arrowheads indicate the **N**-pole of the magnetic needle. The figure shows that the magnetic force has a definite direction at every point and that it acts along lines called *magnetic lines of force*.

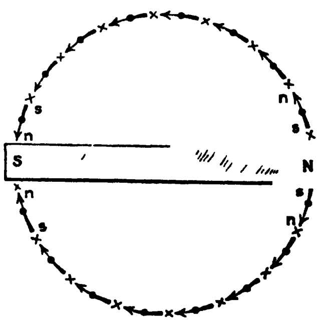


Fig. 25. — Plotting the Position of a Magnetic Needle.

18. The Magnetic Field. — The space which is permeated by the magnetic lines of force surrounding a magnet is conventionally called the *magnetic field of force*, or simply a mag-

netic field. It is also assumed that the magnetic lines of force emanate from the **N**-pole of a magnet, pass through the surrounding medium, reënter the **S**-pole, and complete the path, or circuit, from the **S**-pole to the **N**-pole, through the magnet itself. Every line or curve of magnetic force must have a complete circuit; hence, as already proven, it is impossible to have a magnet with only one pole. *The magnetic lines complete their circuits independently, and never [illegible], cross, or merge into each other.* The internal field is much smaller in cross section than the external field, due to the fact that the steel is a much better conductor of magnetic lines of force than the surrounding medium. Because of this concentration of lines of force inside the magnet they are crowded together where they leave the magnet at the **N**-pole, and where they enter at the **S**-pole. The strong attraction at the poles, and none at the middle of the magnet, is thus accounted for.

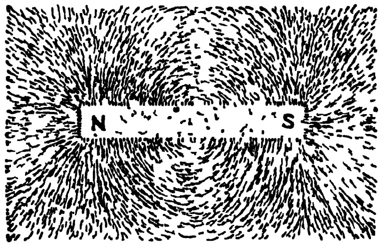


Fig. 26. — Graphical Magnetic Field of a Bar Magnet.

A graphical representation of the magnetic field surrounding a magnet may be produced by placing a sheet of paper over the magnet and sifting fine iron filings over the paper while gently tapping the paper. The filings, being magnetic bodies, arrange themselves in the direction of the magnetic curves or lines of force, producing a field similar to Fig. 26. Other magnetic fields, rendered visible by iron filings, are shown in Figs. 27, 28 and 29.

The student should produce fields similar to Figs. 26 to 29, and of any other possible combinations of magnets that may occur to him. A thorough knowledge of the direction of lines of force, as depicted by the graphical representations of magnetic fields, will greatly assist in the understanding of the phenomena of electromagnetism and electromagnetic induction, to be considered later.

19. Axis and Equator of Bar Magnet. — The straight line joining the **N**- and **S**-poles of a bar magnet is called the magnetic axis (Fig. 30). A line drawn through the neutral point at right angles to the axis is called the magnetic equator. The neutral point may be defined as the position midway between the poles where, by the aid of iron filings, no external magnetism is shown.

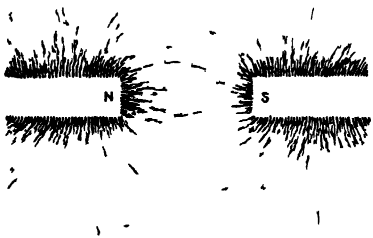


Fig 27 — Graphical Magnetic Field between Unlike Poles

20. Magnetic Bodies Free to Move. — If a graphical magnetic field be made of a bar magnet with a piece of iron lying in the field, it will be noted that the magnetic field is distorted, and many of the lines pass through the piece of iron. Magnetic lines of force always prefer the path of least resistance. If a piece of iron is arranged free to move in the field, it will turn and take up such a position as to accommodate through itself the greatest number of the lines of force. The fundamental principle in many forms of electrical measuring instruments and electromechanical devices is that *a magnetic body, free to move under the influence of a magnetic field, tends to move so as to accommodate, through itself, the greatest number of lines of force of the field.* If the *movable body is a magnet* it moves in a *particular direction,* so that its own internal magnetic lines will be in the same direction as those of the field in which it is placed.

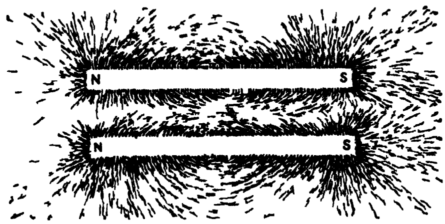


Fig 28 — Graphical Magnetic Field of Two Parallel Bar Magnets with Like Poles Adjacent.

21. Magnetic Induction. — A piece of soft iron, placed in the magnetic field of another magnet, assumes the properties

of the magnet. The iron is the *body under induction,* the magnet the *inducing body,* and the phenomenon is known as *magnetic induction.* It may be defined as the action and reaction which occur when the magnetic lines of force, emanating from a magnetic body, make evident the latent magnetism in another magnetic body, either with or without contact of the bodies. The phenomenon of magnetic induction always precedes the attraction of a magnet for a magnetic body, and takes place through all non-magnetic mediums, whether they are solids, liquids, or gases. Magnetic induction in iron may be explained by the molecular theory, when it is remembered how readily the molecules of soft iron turn on their axes when subjected to a magnetizing force. The methods of magnetization given in ¶ 6 are based on the principle of magnetic induction, which the student should now apply to each case.

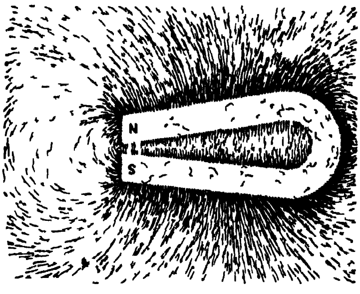


Fig 29 — Graphical Magnetic Field of a Horseshoe Magnet

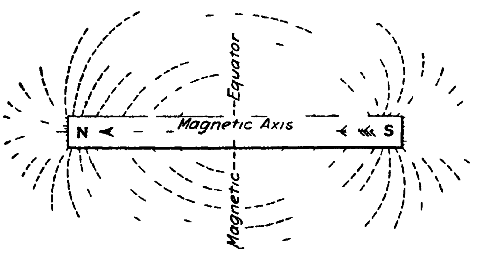


Fig 30 — Conventional Field of a Bar Magnet.

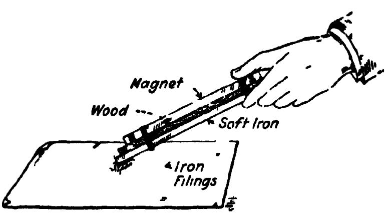


Fig. 31. — Magnetic Induction.

Experiment 5. — Plunge a soft iron bar in iron filings and note that no filings are attracted to it. Bring one pole of a magnet in contact with the iron bar, dip the end of the bar in filings, and note that they are now attracted to it. Remove the magnet from contact with the soft

iron; note that, while most of the filings drop off, there are still a few that cling to the iron. Why? Separate the magnet from the iron bar by pieces of wood, brass, glass, etc., apply the iron to the filings as shown in Fig. 31, and observe their attraction; proving that magnetic induction takes place between bodies in contact or separated from each other.

Experiment 6. — Support an iron rod about six inches long, horizontally in line with, and on the same height as, a poised magnetic needle when it is pointing north and south, but separated from the N-pole of the needle by a small space, as in Fig. 32. With the N-pole of a bar magnet approach the far end of the iron rod, and the needle will be repelled from the iron rod. The iron rod is first magnetized inductively by the needle, the N-pole of the needle inducing a S-pole in the end of the iron nearest to it and a N-pole at the far end. The bar magnet (the inducing body), being stronger than the needle, induces a S-pole in the end of the iron nearer to it and a N-pole in the other end, thus neutralizing the needle's inductive effect by demagnetizing the iron and remagnetizing it in the opposite direction. When the magnetizing body is removed the needle assumes its former position, provided the iron is very soft. This experiment proves that the bar of iron has poles when inductively magnetized.

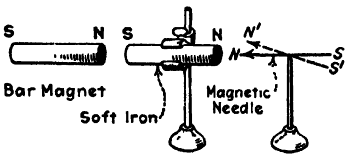


Fig. 32. — Magnetic Induction.

Without the magnet the needle is in the position NS; but when the magnet is brought near the rod, the needle is repelled to position N' S'.

22. Magnetic Screens. — Permit a magnet to deflect a magnetic needle; then interpose any nonmagnetic substance, such as wood, glass, or rubber, between the magnet and the needle; the deflection is not altered. A plate of thick iron, however, when interposed between the magnet and the needle, acts as a *magnetic screen*, reducing the deflection of the needle toward the magnet. The iron plate is magnetized inductively by the magnet on the one side; the needle produces a similar effect on the other side of the plate and, being free to move, deflects slightly, until its lines of force are proportionately accommodated between the earth's magnetism and the magnetism in the iron plate. There is no *magnetic insulator*, that is a material which will stop the lines of force. The method of protecting any device from the

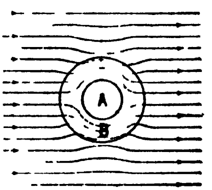


Fig. 33. — Magnetic Screen.

effects of a magnetic field is to use a soft iron screen that would encircle the device, thus conducting the lines of force of the field around it. Thus in Fig. 33, the circular iron screen B carries the magnetic lines of force and leaves the inner region A free from such lines. This principle is utilized in the use of heavy cast iron boxes for certain measuring instruments, to shield them from the effects of a magnetic field.

23. Consequent Poles. — Although two poles is the least number a magnet can have, it may possess any number greater than two. All these poles except the two end poles are called *consequent* poles (Fig. 34). If two *like* poles of a weak and a strong magnet be approached to each other, as a compass needle not free to move and a bar magnet, repulsion will take place up to within a certain distance between the like poles, after which attraction occurs, because the inductive effect of the stronger magnet has demagnetized the weaker magnet and remagnetized it again with opposition polarity. Magnetic needles often have their polarity thus reversed, so that the marked ends point south instead of north. *In making any tests with a needle always allow it to come to rest first in the earth's field, as the polarity may have been reversed since it was last used.*

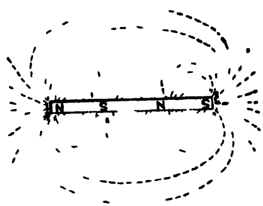


Fig 34 — Bar Magnet with Two Consequent Poles.

With a reversal of polarity sometimes more than two poles are manifest in the body which has had its polarity reversed. In such cases the body will have a number of intermediate or consequent poles and of neutral points; these may be readily shown by plunging its entire length into iron filings.

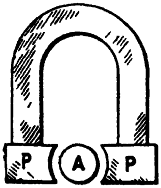


Fig. 35. — Permanent Magnet with Iron Pole Pieces (P) and Armature (A).

24. Pole Pieces and Armatures. — To concentrate and direct the magnetic lines of force, which extend in all directions from the poles of a magnet, *pole pieces* of soft iron (Fig. 35) are fastened to the magnet's poles. An *armature* is a magnetic body placed between or near, but

not touching, the poles of a magnet, and is free to be rotated, as A in Fig. 35, or free to be moved to and from the poles, such as the moving element of a telegraph sounder, or the vibrating arm of an electric bell.

QUESTIONS

1. Explain what you mean by the molecular theory of magnetism. Give sketches.

2. Explain how, by successively breaking up a bar magnet, you support the molecular theory of magnetism. Give sketch.

3. According to the molecular theory of magnetism, explain what you mean by magnetic saturation.

4. Why is it that hard steel makes a better permanent magnet than soft iron?

5. What do you understand by retentivity? Give an example to illustrate your answer.

6. Two bar magnets with like poles adjacent are laid on a piece of cardboard parallel to each other. A horseshoe magnet is placed so that its poles are directly opposite but a little distant from the poles of the bar magnet. Sketch the resultant magnetic field that you would expect to see from this combination if iron filings were used.

7. What is magnetic force? How would you prove its existence and direction around a magnetized steel bar?

8. What is a magnetic field?

9. A piece of steel attracts the N-pole of a magnet. Would this phenomenon positively prove that the steel is magnetized? Give a reason for your answer.

10. What is meant by the neutral point of a bar magnet?

11. Give a concise statement as to the movement of a magnetic body (when free to move) when it is placed in a magnetic field.

12. Cite and illustrate by sketches an experiment to demonstrate the phenomenon of magnetic induction.

13. Apply the principle of magnetic induction to a piece of steel you are required to magnetize by rubbing it from one end to the other with one pole of a bar magnet. Give sketches illustrating the stages of magnetization.

14. Upon testing a bar magnet with iron filings it is found to attract filings at the center and also at each end. How do you account for this? Make a sketch to illustrate your answer.

15. What is a magnetic screen, and for what purpose is it used?

LESSON III

VOLTAIC ELECTRICITY

Electricity — Electrical Effects — Generation of Electric Currents by Chemical Means — A Current of Electricity — Simple Voltaic Cell — The Circuit — Conductors and Insulators — Direction of the Current — Poles and Electrodes of a Cell — Detector Galvanometer — Potential and Electromotive Force — Chemical Action in a Voltaic Cell — Why the Hydrogen Appears at the Copper Plate — Polarization — Table I — On what the Electromotive Force of a Cell Depends — The Electrochemical Series — Table II — Local Action — Amalgamation — Questions.

25. Electricity. — The word *electricity* has been applied to an invisible agent known to us only by the *effects* which it produces, or its various *manifestations.* While the exact nature of electricity is not known the laws governing electrical phenomena are clearly understood and defined, just as the laws of gravitation are known, although we cannot define the nature of gravity. Electricity was assumed by the early scientists to consist of two fluids, which were contained in neutral bodies in equal amounts. When by any means this equality was disturbed in a body, it became *charged* and electrical manifestations occurred. In the light of later scientific knowledge the two-fluid theory has been discarded. Faraday believed that these manifestations were due to a strained condition in the ether which surrounds charged bodies, and this theory of electricity was further developed by Maxwell, who considered the strain to consist in some sort of displacement in the ether.

Recent experiments on electrical discharges through gases, on radioactivity and on X-rays have shown the inadequacy of Maxwell's theory, and have led to its modification which is generally known as the *electron theory.* According to this theory, electricity is corpuscular in nature and of one kind only, the corpusles being negative charges called *electrons.* Following this theory, a neutral body has a normal supply of electrons,

a negatively-charged body has an excess of electrons, and a positively-charged body has a deficiency of electrons. Further, the flow of electricity between two points is generally considered as a transfer of electrons from one point to the other The flow of electricity through a wire is therefore analogous to the flow of water through a pipe, so that electricity can be said to flow through a wire.

26. Electrical Effects. — The manifestations produced by electricity may be divided into two distinct classes. First, *electricity when at rest* is known as *static electricity*, and the bodies electrified are said to be statically charged; the term *electrostatics* applies to this subject. Second, *electricity in motion* differs from static electricity and is treated as a *current of electricity*.

Electricity in motion produces magnetism, which has been termed *electromagnetism*, it dissociates chemical solutions, which has been termed *electrolysis*, it produces heat in wires, and occasions other effects, such as *electrical waves*, etc. All these phenomena are very intimately associated with each other, and are due to the one invisible agent, *electricity*. In this book we will study primarily *currents of electricity* and their effects, which form the basis of a great many practical electrical applications.

27. Generation of Electric Currents by Chemical Means. —

Experiment 7. — Fill a tumbler two-thirds full of dilute sulphuric acid (one part acid to twenty parts water) and partially immerse in the solution a strip of sheet zinc, say one inch wide by five inches long. Bubbles of gas immediately collect on the zinc, and then, detaching themselves, rise to the surface of the liquid, being rapidly replaced by other bubbles as the action continues. These bubbles of gas are hydrogen (one of the gases of which water is composed), and when collected, by displacing water in an inverted test tube held over them, this gas may be ignited and will burn with a pale bluish flame. If the zinc remains in the acid for some time, it wastes away or is dissolved in the liquid.



Fig. 36. — Copper and Zinc in Acidulated Water.

Experiment 8. — Place a strip of copper, of about the same dimensions, partially in the acid as before. No bubbles of gas are seen rising from the copper. If this metal is allowed to remain for some time it will not apparently be acted upon by the acid.

Experiment 9. — Place the strips of copper and zinc in the tumbler of acid, not permitting them to touch each other, in or out of the liquid. Hydrogen

gas continues to rise from the zinc as before, but there is no action on the copper plate. Bring the outer extremities of the copper and zinc strips into contact (Fig. 36), and torrents of bubbles are *now seen to rise from the copper strip*, in addition to the bubbles rising from the zinc strip. If collected, the gas evolved from the copper proves to be hydrogen, the same as that rising from the zinc. If the action is permitted to continue for some time, upon examination the zinc is found to have wasted away, while the copper remains unchanged. Break the external contact between the plates and the action at the copper instantly ceases, but the zinc wastes away as before.

Experiment 10. — Remove the zinc strip from the liquid, and while it is still wet with the acid rub over its surface a little mercury. Upon being replaced in the solution the acid does not attack it. Repeat Experiment 9 with this "amalgamated zinc" (see ¶ 42), and note that now bubbles rise only from the copper plate, when the ends of the two strips are brought together, and that none rises from the zinc plate, but that it is still the zinc plate which wastes away.

Experiment 11. — Connect wires of any metal to the copper and zinc plates, being sure that you have bright metallic contacts. Bring the extremities of these two wires together after they have been brightened and hydrogen gas is seen to rise from the copper plate as before, while there is no action at the zinc.

When the wires are separated the action ceases, but commences again as soon as connection is made. Interpose *between* the two connecting wires pieces of glass, mica, rubber, paper, wood, porcelain, etc., or connect the two plates by a bridge made of any of these materials; *no action appears at either plate.*

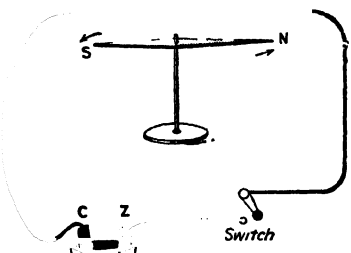


Fig. 37. — Deflection of a Magnetic Needle by a Current Flowing in a Wire.

It thus requires a connection between the two plates to cause chemical action, and this connection must be of a particular kind. It would seem that the plates exert an influence upon each other through the connecting wire. We will now ascertain whether the connecting wire possesses any extraordinary qualities when thus connected with these dissimilar plates.

Experiment 12. — Set up a poised magnetic needle. When pointing north and south place above and parallel to it a portion of the connecting wire used in the last experiments (as in Fig. 37).

When the ends of the wires are brought together the needle immediately turns upon its axis at right angles, or nearly so, to the wire, after a few vibrations, and remains in this position until the connection is broken, when it assumes its normal position. The deviation of the needle from its original position is termed the *deflection of the needle.* Note that chemical action continued in the tumbler as long as the needle was deflected, and at the expense of the zinc rod.

Experiment 13. — With the wire arranged as in Experiment 12, interpose pieces of tin, steel, copper, iron, lead, gold, brass, aluminum, etc., between the connecting wires, and the needle is deflected as before. When pieces of paper, glass, wood, mica, etc., are interposed, however, there is no deflection of the needle, which again proves the necessity of a suitable connector between the copper and zinc plates.

Experiment 14. — Test an iron rod by iron filings for magnetism. It does not attract them. Wind a few turns of cotton-covered wire around the iron rod and plunge it into the filings, after first connecting the ends of the wires to the two plates in the tumbler. Filings are now attracted to the iron core, but drop off when the connection to the plates is broken. This, then, is a temporary magnet, produced by the magnetic properties possessed by the wire.

28. A Current of Electricity. — From the foregoing experiments it appears that when zinc and copper are immersed in an acid solution and connected by a wire, the wire possesses unusual *magnetic properties.* The cause of this magnetic effect, and other effects associated with it to be noted later on, is attributed to electricity, and the property possessed by the wire is said to be due to a transference of electricity from one plate to the other, the wire acting as a conducting medium. When we speak of a current "flowing through the wire from plate to plate," it is simply a convenient expression used to describe the phenomena involved, although we may not know what actually transpires.

An ebonite or glass rod is *electrified* when rubbed with flannel, silk, etc., and possesses the power of attracting light bodies to it, and also of attracting or repelling another similarly electrified rod, according to the nature of its *electrification.* When the portion of a rod so electrified is touched by the hand, or

other conductor, the electrification disappears and the body is said to be discharged. The two plates in the tumbler may be said to be electrified to different degrees of electrification, and when they are connected by a wire, the electrification discharges from the higher to the lower electrified plate. The action of the acid upon one plate more than the other, however, tends to keep the plates at different states of electrification, and the successive discharges through the connecting wire become so intensely rapid that they form practically a *continuous current* of electricity.

29. Simple Voltaic Cell. — When two *dissimilar* metals are partially immersed in a solution, which is capable of acting chemically upon one of them more than upon the other, the combination constitutes a voltaic cell. The name *voltaic* is derived from an Italian physicist, Volta, who first discovered the cell in 1800. It is sometimes called a galvanic cell, after Volta's contemporary, Galvani. Correctly speaking, the word *battery* applies to a number of such cells connected together, though the name is commonly applied to a single cell. The solution in which the metals are immersed is called the *electrolyte*, or exciting fluid, or excitant. The term *primary cell* is generally used to signify any cell that generates an electric current directly from the chemical action of an electrolyte on two dissimilar materials.

30. The Circuit. — Considering again our simple voltaic cell (Fig. 37), the term *circuit* is applied to the *entire path* through which the transference of energy takes place, or the current of electricity is supposed to flow, and the wire joining the plates is called the *conductor*. The circuit, then, consists of not only the conductor between the plates outside of the cell, but the liquid conductor between the plates inside of the cell; hence we speak of the *external* circuit and the *internal* circuit.

The *complete circuit* includes the conducting wire, the two plates which act as conductors, and the liquid between them. Bringing the two extremities of the wires into contact is called *making*, or *closing* the circuit, and separating the wires is termed *opening*, or *breaking* the circuit.

31. Conductors and Insulators. — The substances which, when interposed between the terminal wires of a voltaic cell,

do not interfere with the deflection of the magnetic needle (as the metals) are known as *conductors* of electricity, because they allow the current to flow through them, while other substances so interposed, as glass, wood, mica, etc., interfere with the action in the cell and upon the needle, and are therefore called *insulators*. All substances resist, or oppose, the flow of electricity, those substances known as conductors (as the metals) offering considerable less opposition than those classed as insulators. This opposition is termed *electric resistance* (¶ 62), the amount of electric current depending upon the resistance in the circuit, as well as upon the electromotive force (¶ 35). A classified list of conductors and insulators is given in ¶ 64.

32. Direction of the Current. —

Experiment 15. — Place the conducting wire of a voltaic cell over and parallel with a magnetic needle when it is pointing north and south (north is at the left in Fig. 38) Close the circuit and note whether the **N**-pole of the needle points east or west when the current is flowing. Say it is deflected to the east. Now reverse the wire connections at the battery plates (that is, connect the end of the wire which was attached to the zinc to the copper, and vice versa); the **N**-pole of the needle now points west if the wire is held as before, Fig. 39.

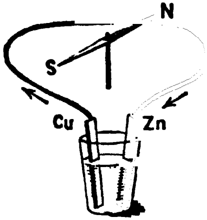


Fig. 38. — Direction of Current Flow.

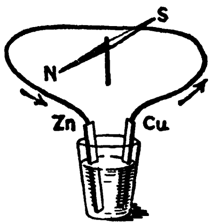


Fig. 39. — Direction of Current Flow.

This experiment indicates that electricity produces a magnetic force around a wire, and, on account of the behavior of the needle, that this force has direction. In consequence the flow of electricity has direction. Electricians have agreed to assume that the electricity flows from the *copper* terminal *to the zinc* terminal *through the conducting wire*, and from the *zinc plate* to the *copper plate through the solution*.

33. Poles and Electrodes of a Cell. — The metal plates or elements suspended in the liquid, are termed the plates, or *electrodes*, and the conducting liquid the electrolyte. The copper plate is called the *negative plate* or electrode, and the

zinc plate the *positive plate* or electrode, while the external end of the copper plate is called the *positive pole,* and the external end of the zinc plate, the *negative pole* (Fig. 40). If we bring the + (plus sign for the positive) and – (minus sign for negative) wires from a cell together making the circuit, the current passes from the + (copper) to the – (zinc) terminal across the junction, and also from the + plate (zinc) to the – plate (copper) through the cell. In any electro-generative device that pole is considered *positive from which the current flows,* and that pole *negative to which the current flows.* As an aid in remembering the terminals or poles consider the chemical abbreviation for zinc, namely *Zn* and that the word *negative* begins with the letter *n.* In any cell the *positive plate* (generally zinc) is the one most acted upon, the current being supposed to start at the surface of this plate, travel through the solution to the copper plate, and from the copper terminal to the zinc terminal through the external circuit.

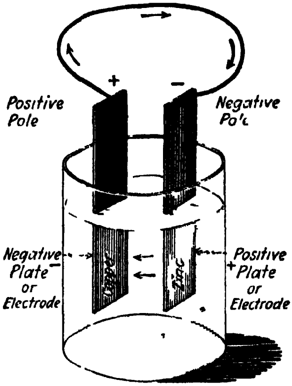


Fig. 40. — Nomenclature of a Voltaic Cell.

34. Detector Galvanometer. —

Experiment 16. — From Experiment 15 it was seen that if a current passes over a needle it is deflected to the east or west, according to the direction of the current. The student should now prove that the needle is deflected oppositely if the wire be held underneath, but parallel to it, according to the direction of current in the wire. Note also that for the *same direction* of current underneath the needle as above it, the deflection is opposite to what it previously was. Now bend the wire around the needle, at rest, parallel to it, so that the current flows over the needle and under the needle in opposite directions. The deflection is now in the same direction, and *greater* than before. Make several con-

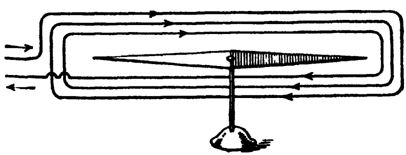


Fig. 41. — Simple Form of Detector Galvanometer.

volutions (Fig. 41) and the deflection is further increased. A few turns of wire wrapped around a pocket compass, parallel to the needle when it is pointing north and south, constitutes a simple form of *detector galvanometer*, and when inserted in a battery circuit will indicate by the deflection of the needle that a current is flowing. Various types of galvanometers are described in Lesson XVI.

35. Potential and Electromotive Force. — Suppose two vessels partially filled with water are joined by a pipe and that the water is at the same level in both. The connecting pipe is full of water, yet there is *no current* of water flowing through the pipe because the pressure at each end is *the same*. When one vessel, A (Fig. 42), is raised above the other, B, then there is a *difference in pressure* between the two ends of the pipe, and a current of water *flows* from the *higher* to the *lower* level, due to this difference of pressure (or head) between the two points. It is not necessary to know the height of vessel A or B above the sea level, but the height or head, H, between the two vessels. Similarly, if two points on a copper bar are elevated to the same temperature there is no transference of heat from one point to the other. If, however, one point is at a higher temperature than the other, there is then a difference in temperature between the points and a transference of heat from the point of higher to the point of lower temperature.

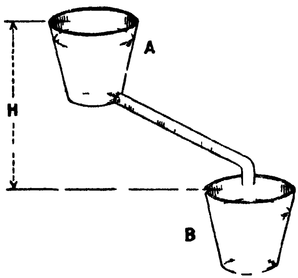


Fig. 42 — Water Analogy for Potential Difference

The word *potential* as used in an electric sense is analogous to pressure in gases, head in liquids, and temperature in heat. In the voltaic cell, then, we have two bodies raised to different electrical potentials (see ¶ 28), and to the difference of potential between them is due the current flowing through the wire connecting the plates. The greater this difference of potential the greater the current, or effect of the current produced.

Potential is the force which moves electricity through the circuit. The total force required to cause the current to flow through the entire circuit is called the *electromotive force*, whereas a *difference of potential* would exist between two points

in a circuit, which would cause the current to flow just between these two points. Electromotive force (abbreviated E. M. F.) is the total difference of potential (abbreviated P. D.) that is maintained in any circuit.

Experiment 17. — Insert two similar pieces of copper or of zinc in the tumbler of acidulated water and test for a current by a detector galvanometer. The needle is not deflected. The similar plates being both electrified to the same degree, there is no difference of potential between them, hence no current. This is analogous to the two vessels of water placed on the same level.

36. Chemical Action in a Voltaic Cell. — A continuous potential difference is maintained between the zinc and copper electrodes of a voltaic cell chiefly by the action of the exciting liquid upon the zinc. The chemist symbolizes sulphuric acid as H_2SO_4, meaning that it is composed of two parts hydrogen (H_2), one part sulphur (S), and four parts oxygen (O_4). The SO_4 part of the acid has a strong affinity for the zinc, and when the cell circuit is completed, attacks the zinc and forms zinc sulphate ($ZnSO_4$), which is dissolved in the water. For every SO_4 part of the sulphuric acid which unites with the zinc, two parts of hydrogen gas are liberated, which escape from the solution as already noted in the experiments. The zinc thus replaces the hydrogen in the acid, setting it free. The chemical action may be expressed as follows:

$$Zn \quad + \quad H_2SO_4 \quad = \quad ZnSO_4 \quad + \quad H_2.$$

Zinc and sulphuric acid produce zinc sulphate and hydrogen.

Every time the circuit of a cell is completed, and as long as it is completed, this chemical action takes place, the zinc gradually wasting away; also the power of the acid to attack the zinc gradually becoming exhausted. Thus the electrical energy is maintained in the external circuit to perform useful work by the expenditure of so many pounds of zinc and acid inside the cell. In other words, the combination of zinc with the acid radical, SO_4, of the sulphuric acid liberates energy which manifests itself as an electric current in the circuit. The chemical energy of the voltaic cell is changed into electrical energy somewhat like the chemical energy contained in a lump of coal is converted into kinetic energy when burned under a steam boiler.

37. Why the Hydrogen Appears at the Copper Plate. — As already stated, when zinc is immersed in sulphuric acid, hydrogen is liberated and rises in bubbles to the surface of the solution. In the voltaic cell it was noticed that the hydrogen bubbles rose from the copper, yet no bubbles were seen to pass through the solution. Many chemists believe that the instant an element is liberated from a compound (as the H_2 from the H_2SO_4) it possesses unusual readiness to enter into combination with other molecules. The action that takes place in a cell may be pictured as follows: at the instant the circuit is closed

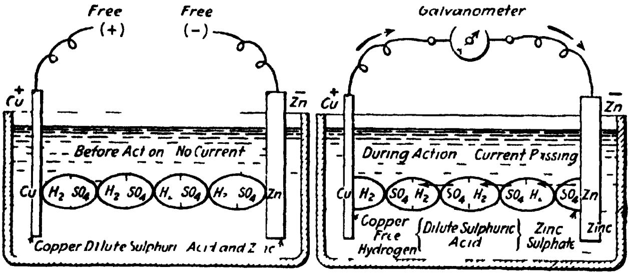


Fig 43 — The Chemical Action in a Voltaic Cell when the Circuit is Closed.

The molecules of sulphuric acid are represented by the ovals

(Fig. 43) the SO_4 of molecule 1 unites with a molecule of zinc, setting free a molecule of hydrogen; this instantly unites with the SO_4 of molecule 2, forming a new molecule of H_2SO_4 and setting free the H_2 of molecule 2. This action continues until the last free molecule of H_2 appears at the copper plate and rises to the surface.

38. Polarization. —

Experiment 18. — Connect a voltaic cell to a detector galvanometer wound with a few turns of wire and note the angle of deflection of the needle. Allow the current to flow for a while, and note that the deflection gradually falls and becomes much less than at first. Brush off the bubbles adhering to the copper plate with a swab and the deflection is increased, thus indicating a stronger current; but it soon falls again when the copper plate becomes coated with the hydrogen gas.

The copper plate coated with hydrogen becomes practically a hydrogen plate. Now the effect of using a plate of

hydrogen with zinc in a cell would be to set up a current from the hydrogen to the zinc inside the cell and from the zinc to the hydrogen outside of the cell. As this tendency acts against the direction of the ordinary copper-to-zinc current it weakens the current from the cell. When the cell becomes weakened in this manner by a coating of hydrogen bubbles on the negative plate it is said to be polarized and the phenomenon is called *polarization*. Polarization, then, must be properly overcome by arresting the bubbles in some manner, in order to permit the cell to give a strong current as long as any zinc remains to be acted upon. The employment of different methods of preventing polarization has resulted in the numerous types of cells now on the market.

The following test made on a Leclanché cell (¶ 51) will illustrate the phenomenon of polarization. The cell was connected to a circuit of low resistance, and readings of a voltmeter (¶ 129) were taken at one-minute intervals for five minutes, during which time the E. M. F. dropped from 1.41 to 0.63 volts. The cell was then allowed to stand on open circuit for five minutes, and then one-minute readings were taken to note its *recuperation*. At the end of the fifth minute the former E. M. F. was not regained, but only 1.18 volts. One-half hour after the test a measurement showed the original E. M. F. of 1.41 volts.

Table I. Polarization Test

Discharge		Recuperation	
0 minutes,	1.41 volts	0 minutes,	0.63 volts
1 "	1.03 "	1 "	0.87 "
2 "	0.80 "	2 "	0.97 "
3 "	0.70 "	3 "	1.06 "
4 "	0.65 "	4 "	1.14 "
5 "	0.63 "	5 "	1.18 "

39. On what the Electromotive Force of a Cell Depends. — If two plates of zinc are immersed in an acid solution (Experiment 17) and connected, there is a tendency to produce opposite currents, which neutralize each other; since there is no difference of potential between them, no current flows. *The essential parts of any cell, then, are two dissimilar metals immersed in an acid solution, one of which is more readily acted upon by the acid than the other.* The greater the difference in intensity of chemical action the greater the difference of potential, and the greater the current strength.

Other metals than copper and zinc may be used in cells, and as acids attack the different metals with varying intensities of chemical action, some combinations will produce better results than others. For example, a cell composed of zinc and lead plates, immersed in dilute sulphuric acid, will not deflect a magnetic needle to so great an angle as a zinc-copper cell of the same size, because a higher difference of potential is set up between zinc and copper than between zinc and lead.

The electromotive force of a cell is dependent also on the solution used to attack the zinc, so that the same battery plates immersed in different acids would indicate different potential differences for the combination in the various solutions. Using the same solution, however, this force is independent of the size of the plates, *a small battery having the same potential difference, or E. M. F., as a large one of the same kind.*

40. The Electrochemical Series. — In the following list of substances, known as the *electrochemical series*, those most acted upon (electropositive plates) by dilute sulphuric acid are placed at the left-hand of the list, while those least acted upon (negative plates) are placed at the right-hand end of the list. The arrangement would be different for other acids used as electrolytes.

Table II. The Electrochemical Series

Direction of current through external circuit

←

Positive plates	Zinc	Iron	Tin	Lead	Copper	Silver	Platinum	Carbon	Negative plates

→

Direction of current through solution

The difference of potential in a lead-silver cell would be less than in a lead-carbon cell, while an iron-carbon cell would have a greater P.D., and a zinc-carbon cell still greater. For this reason zinc and carbon, being cheap materials, are extensively used in batteries. The arrows indicate the direction of current through the internal and external circuits. In a lead-carbon cell the carbon would be the positive and the lead

the negative terminal; while in a lead-zinc cell the lead is the positive terminal and the zinc the negative terminal. Considering the plates in the list, any substance is *positive* to any substance which *follows* it and *negative* to any *preceding* it. The difference of potential between zinc and lead immersed in a solution of sulphuric acid is 0.51 volt, that between zinc and copper is 1.01 volt, and that between zinc and silver is 1.21 volt.

Experiment 19. — Using similar-sized strips of lead, copper, carbon, and zinc, make up some different cells with dilute sulphuric acid. Connect each combination to the detector galvanometer and note the direction that the needle swings, the value of the deflection, and to which terminal each plate was connected. Note that when *lead* is connected to the *same terminal* of the galvanometer, and *carbon* used with it, the deflection is in the *opposite direction* to that when *zinc* is used with *lead*, which illustrates that in one instance the current leaves the lead terminal (+), and in the other instance flows to it (-).

Experiment 20. — Connect a galvanometer wound with *many turns* of *fine wire* to a voltaic cell and note the value of the needle's deflection. Slowly withdraw the plates from the liquid and you note that the deflection of the needle remains the same until the circuit is broken at the surface of the liquid. This proves that the E. M. F. is independent of the area of the plates immersed (see ¶ 39). Move the plates farther apart or closer together and the deflection is not changed, if the galvanometer is wound as above. The E. M. F. of a cell is independent of the distance between the plates.

Experiment 21. — Perform Experiment 20 again, using a galvanometer wound with a *few turns* of comparatively *heavy wire* instead of the one with many turns of fine wire. This type of galvanometer indicates the amount of electric *current* instead of the electric *pressure*, as in Experiment 20. Observe that the amount of current that will flow from a cell is dependent upon the area of the plates immersed and the distance between them.

41. Local Action. — When a piece of pure zinc (difficult to obtain) is used in a cell there is no action at the zinc except when the cell is in use. The ordinary commercial zinc contains many impurities, such as small particles of carbon, iron, tin, lead, etc., and when a rod of such zinc is placed in a cell these foreign particles form numerous local voltaic cells on the surface of the zinc inside the cell, with the result that the zinc is being continuously eaten away, whether the cell is in action or at rest. These small currents divert just so much strength from the regular battery current, thereby weakening it. Fig. 44

illustrates a magnified particle of iron on a zinc rod, and a local current would flow from the zinc to the iron through the solution and from the iron to the zinc across the junction. This is known as *local action.* In some cells local action is also caused by a difference in the density of the liquid at various parts of the cell. In this case the zinc near the top of the liquid is ordinarily wasted away and may be entirely eaten off.

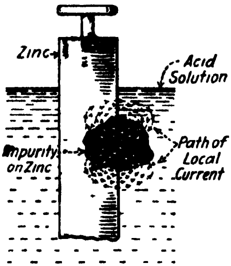


Fig. 44. — Local Action.

42. Amalgamation. — Local action may be prevented by thoroughly cleaning the zinc with sandpaper, then immersing it in dilute sulphuric acid, and while still wet applying mercury (quicksilver) by means of a rag swab. A bright amalgam is formed over the surface of the zinc and it is said to be *amalgamated.* The foreign particles in the zinc are either protected from the action of the acid, or are carried down to the bottom of the cell. The mercury does not prevent the zinc from being dissolved during the action of the cell, but continues to re-form an amalgam as the zinc wastes away. Zinc for battery plates is sometimes cast with a small percentage of mercury in its composition.

QUESTIONS

1. Explain what you understand by the word *electricity.*
2. How does electricity manifest itself?
3. What is the action of dilute sulphuric acid on zinc?
4. What is a simple cell?
5. Explain the action in a simple voltaic cell. Give sketch.
6. Give your idea of a " current " of electricity.
7. What is an electrolyte?
8. What is meant by an open and and by a closed circuit?
9. Distinguish between the internal and external circuit of a cell.
10. What is a detector galvanometer, and for what purpose is it used?
11. What are insulators?
12. What is meant by a good conductor?
13. State an experiment you would make to determine whether a body was an insulator or a conductor.
14. Give a reason for attributing direction to a current.

15. Which way does a current flow inside a voltaic cell?

16. Sketch a simple voltaic cell, name all the parts, and show the direction of the current in the internal and external circuits.

17. Distinguish between poles and plates.

18. Which is the negative electrode in a lead-copper cell using H_2SO_4?

19. Which is the positive plate in a lead-iron cell using sulphuric acid?

LESSON IV

PRIMARY CELLS

Primary Cells — Open-Circuit Cells — Closed-Circuit Cells — Remedies for Polarization — Bichromate Cell — Fuller Bichromate Cell — Bunsen and Grove Cells — Daniell Cell — Leclanché Cell — Carbon Cylinder Cell — Edison-Lalande Cell — Dry Cells — Classification of Primary Cells — Electromotive Force of Some Cells — Clark Standard Cell — Weston Standard Cell — The Effect of Temperature on Voltage — Chemicals for Cells and Their Chemical Symbols — Questions.

43. Primary Cells. — *Primary* cells are composed of two dissimilar metals or materials immersed in an acid solution (¶ 29) which acts chemically on one of the metals or materials more readily than it does on the other. Through this difference in chemical action on the two materials, an E. M. F. is maintained which will force an electric current through an external circuit. Thus, the chemical energy is converted into electrical energy; the positive electrode, generally zinc, being consumed or used up in producing the current. When the zinc has all been consumed, the cell can be renewed by putting a new zinc and fresh electrolyte in the cell, after which it is again ready to furnish a current.

There are other cells, known as *secondary* cells (storage batteries or accumulators, Lesson XII), which can be renewed without adding new electrolyte or plate material — they are restored to their original state by sending a current through them in a direction opposite to the current supplied by the cell.

A good primary battery should have the following qualifications:

Its electromotive force should be high and constant.

Its internal resistance (¶ 72) should be small.

It should give a constant current; therefore it must be free from polarization and not liable to rapid exhaustion.

It should be inexpensive and of durable materials.

It should be perfectly quiescent when its circuit is open.

Primary cells are divided into two general classes, according to the manner in which they are to be used, namely *open-circuit* cells and *closed-circuit* cells.

44. Open-Circuit Cells. — Open-circuit cells are used for *intermittent work*, where the cell is in service for short periods of time, such as for electric bells, telephony, and electric gas lighting. In cells of this class polarization does not have much opportunity to occur, since the circuit is closed for such a short period of time; hence, these cells are always ready to deliver a strong current when used intermittently. If kept in continuous service for any length of time the cell soon polarizes or "runs down," but will recuperate after remaining on open circuit for some little time.

45. Closed-Circuit Cells. — In the *closed-circuit* type of cell *polarization is prevented* by chemical action, so that the current will be constant and steady till the energy of the chemicals is nearly expended. This type of cell is adapted for furnishing current continuously, as in the service of small lamps and motors, telegraphy, fire-alarm signals, electroplating, etc.

46. Remedies for Polarization. — In the simplest form of cell, using zinc, copper and dilute sulphuric acid, no attempt has been made to prevent polarization (¶ 38); hence it will quickly polarize when the circuit is closed for any length of time, and may be classified as an open-circuit cell. When polarization is remedied by chemical means the chemical added is one that has a strong affinity for hydrogen and will combine with it, thus preventing the covering of the negative plate with the hydrogen gas. The chemical used for this purpose is called the *depolarizer* and may be used either in a *solid* or *liquid* form. This choice gives rise to several forms of cells, such as cells with a single fluid, containing both the acid and the depolarizer; cells with a single exciting fluid and a solid depolarizer; and cells with two separate fluids.

In the *double-fluid* form of cell the zinc is immersed in the liquid (frequently dilute sulphuric acid) to be decomposed by the action upon it, and the negative plate is surrounded by the liquid depolarizer, which will be decomposed by the hydrogen gas it arrests, thereby preventing polarization. The two liquids are sometimes separated by a porous partition of un-

glazed earthenware, keeping the liquids from mixing, except very slowly, but not preventing the passage of hydrogen ions carrying charges of electricity.

Experiment 22. Place sufficient mercury in a small battery jar to cover the bottom and fill the jar with a sal-ammoniac solution. Make the connection with the mercury by a piece of rubber-covered wire. Suspend a piece of zinc from the top of the jar to complete a zinc-mercury cell. Connect the cell to a current galvanometer and note the decreasing deflection of the needle, due to polarization. When the cell becomes sufficiently polarized drop into the solution a piece of mercuric chloride ($HgCl_2$) the size of a pin-head. The galvanometer needle instantly shows a much larger deflection. The hydrogen has been removed by the chlorine in the mercuric chloride. When the chloride becomes exhausted polarization sets in again. The mercuric chloride is thus a chemical depolarizer.

47. Bichromate Cell. In the bichromate cell polarization is prevented by chemically arresting the hydrogen gas, so that it never reaches the negative plate. The same will be true of most of the cells now to be described. Bichromate of soda or bichromate of potassium is the depolarizer, to which is added water and sulphuric acid for attacking the zinc. The bichromates are rich in oxygen, for which hydrogen has a strong affinity. Carbon and zinc plates are used, and this type is made up in several forms termed *chromic acid cells*.

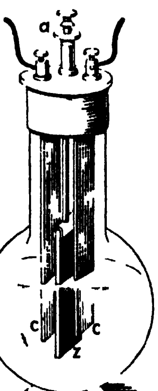


Fig. 45. — Grenet Cell.

Zinc and carbon in bichromate solution

In the Grenet (Gren-ā') form a zinc plate is suspended by a rod between two carbon plates, Fig. 45, so that it does not touch them, and when the cell is not in use the zinc is withdrawn from the solution by raising and fastening the rod, a, by means of a set-screw, as the acid attacks the zinc when the cell is on open circuit. This cell has an E. M. F. of two volts at first, and gives a strong current for a short time, but the liquid soon becomes exhausted, as will be indicated by the gradual change in the color of the solution from an orange to a dark red. The zinc is well amalgamated and is kept out of the solution except when in use. It is a good type of cell for experimental work, and about two

cells would perform many of the experiments in this book. A larger battery of six cells is shown in Fig. 46; four cells are in

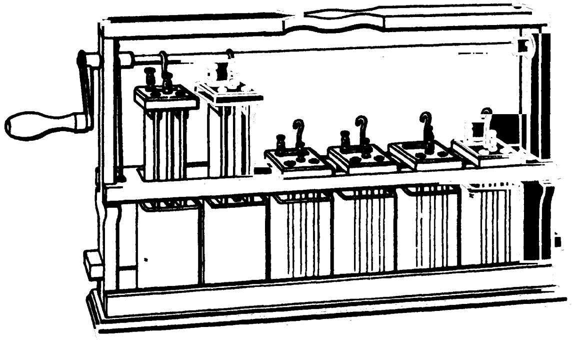


Fig. 46. — Plunge Battery.
The elements of all cells can be raised simultaneously by turning the crank.

use while the elements of the others are suspended from the cross rod.

To make a solution for a bichromate cell take 3 ounces of finely powdered bichromate of potash and 1 pint of boiling water; stir with a glass rod, and after it is cool add slowly, stirring all the time, 3 ounces of sulphuric acid. The solution should not be used until cool. In mixing a battery solution always *pour the acid* gently *into the water*, while stirring, to dissipate the heat. *Never pour water into acid*. If bichromate of soda is used instead, take 4 ounces of bichromate of soda, $1\frac{1}{4}$ pints of boiling water, and 3 ounces of sulphuric acid.

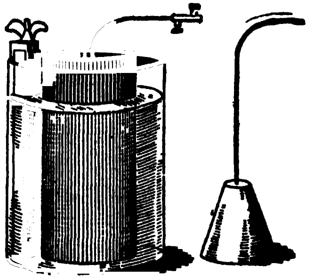


Fig. 47. — Fuller Cell.
Zinc in dilute H_2SO_4 in porous cup, carbon in bichromate solution

48. Fuller Bichromate Cell. — The Fuller double-fluid cell has the advantage over the Grenet type, in that the zinc is always kept well amalgamated and does not require removal from the solution. A pyramidal block of zinc, to which a metallic rod covered with gutta-percha is attached, is placed

in the bottom of a porous cup (Fig. 47) and an ounce of mercury is poured in. The cup is filled with a very dilute solution of sulphuric acid and water, and then placed in a glass or earthen jar containing the bichromate solution and the carbon plate. The acid diffuses through the porous cup rapidly enough to attack the zinc, which, being well amalgamated, reduces local action. The hydrogen travels from the zinc through the porous cup and combines with the oxygen in the potassium bichromate. The E. M. F. is about two volts, and the cell is used for open-circuit or semi-closed circuit work.

49. Bunsen and Grove Cells. - The Bunsen and Grove cells are of the two-fluid type, the solutions being separated by a porous partition. The Bunsen cell (Fig 48) has a bar of carbon immersed in strong nitric acid contained in a porous cup. This cup is then placed in another vessel containing dilute sulphuric acid, and immersed in the same liquid is a hollow, cylindrical plate of zinc, which nearly surrounds the porous cup. The hydrogen, starting at the zinc, passes through the porous partition, and immediately enters into chemical action with the nitric acid, so that none of it reaches the carbon. There are produced by this action water, which in time dilutes the acid, and orange-colored poisonous fumes of nitric oxide, which rise from the cell. If the nitric acid first be saturated with nitrate of ammonia, the acid will last longer and the fumes will be avoided. Strong sulphuric acid cannot be used in any battery; generally 12 parts by weight, or 20 by volume, of water are mixed with one part of sulphuric acid.

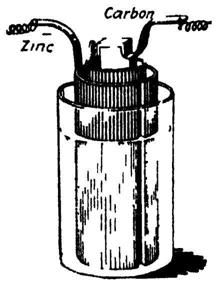


Fig 48 Bunsen Cell.

Carbon in porous cup with HNO_3 zinc in dilute H_2SO_4

Grove used a strip of *platinum* instead of *carbon* in his cell A solution of bichromate of potassium (as in ¶ 47) is frequently substituted for the nitric acid in the porous cup, thereby avoiding disagreeable fumes. The Bunsen and Grove cells produce powerful and constant currents, and are well adapted for experimentation, but they require frequent attention, and are expensive, so that they are little used for work of long duration The E. M. F. of these cells is about 1.9 volts.

50. Daniell Cell. — The Daniell cell is made in many forms and is called by various names, such as Gravity cell (Fig. 49), Bluestone cell, Crowfoot cell, etc. It is a closed-circuit cell and is often used in practice for giving constant currents for long periods. Zinc and copper are the elements of the cell.



Fig. 49 — Gravity Daniell Cell

An explanation of the theory of a simple form, Fig. 50, will answer for all forms of this class; the elements are separated by a thin partition of unglazed pottery. On the zinc side of the partition is put dilute sulphuric acid (H_2SO_4), or simply water if the cell is not required for immediate use; on the copper side is placed sulphate of copper ($CuSO_4$) dissolved in water, together with some sulphate of copper crystals (bluestone) to maintain the supply of copper sulphate solution. When the circuit is closed, as shown at the right, the zinc combines with the (SO_4) of the sulphuric acid, forming sulphate of zinc ($Zn\ SO_4$), and thus sets free the two atoms of hydrogen (H_2).

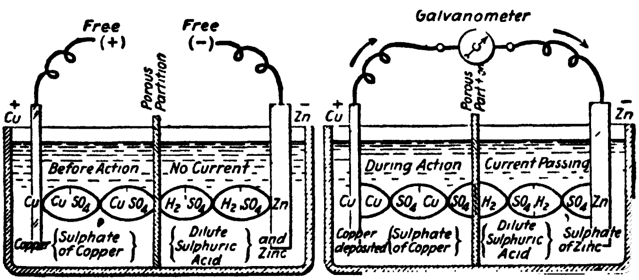


Fig. 50. — Chemical Action in the Daniell Cell.

This hydrogen gas passes through the porous partition, but instead of collecting on the sides of the copper plate, it meets with the sulphate of copper ($CuSO_4$), and having a greater natural affinity for the (SO_4) than the copper (Cu) possesses, it displaces the copper and forms sulphuric acid (H_2SO_4), setting free pure metallic copper, which is deposited upon the copper plate. This continuous extraction of metallic copper from the

solution would soon weaken it, were it not for the fact that the copper crystals dissolve and thus automatically keep the solution saturated. To maintain a constant current for an indefinite time, therefore, it is only necessary to keep up the supply of copper crystals and zinc. The cell has an E. M. F. of about 1.1 volts and gives a small but steady current.

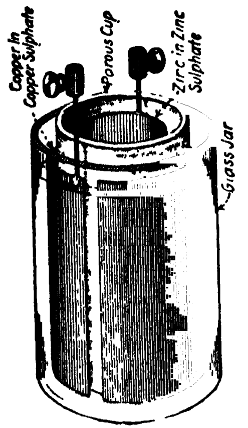


Fig. 51. Student's Porous-Cup Daniell Cell.

A student's small Daniell cell is shown in Fig. 51. It is of the double-fluid type. A rod of well-amalgamated zinc is immersed in a solution of dilute sulphuric acid contained in the porous cup. The porous cup is placed in a glass jar containing a saturated solution of copper sulphate and a copper electrode that surrounds the porous cup. The sulphuric acid changes to zinc sulphate during operation, and consequently the cell may also be set up originally by using zinc sulphate instead of sulphuric acid.

The cell gives a constant potential of about 1.1 volts; the current on short-circuit is small, but since polarization is eliminated it is a good cell to use for electrical measurements where a constant source of E. M. F. is required; see Lesson XIX.

51. Leclanché Cell. – The Leclanché cell is an example of the single solution type, and utilizes a solid depolarizer surrounding the negative element, which is generally carbon, the positive element being zinc. The liquid used is a strong solution of ammonium chloride, commonly known as sal-ammoniac, and much resembles table salt. In the porous-cup type of cell, Fig. 52, a carbon slab C is placed in the porous cup P and surrounded by a mixture of small pieces of carbon and manganese dioxide, the top being covered by means of pitch, leaving one or two small holes for air and gas to pass through. The depolarizer will take care of a limited amount of the hydrogen produced when the cell is on closed circuit, but if the circuit be closed for any length of

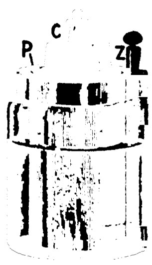


Fig. 52. — Leclanché Cell.

time polarization occurs. The cell is thus of the open-circuit class, and zinc is dissolved only when the cell is being used. This cell is often used for bell work, and requires very little attention. Water must be added as the solution evaporates, and the zinc rod replenished when necessary. The E. M. F. is about 1.4 volts and the internal resistance is about 4 ohms.

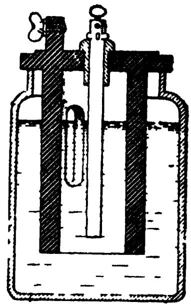


Fig. 53. — Carbon Cylinder Cell

To set up the Leclanché cell, place six ounces of ammonium chloride (sal-ammoniac) in the glass jar, pour in water until the jar is one-third full, and stir thoroughly. Insert the porous cup and add water if necessary until the level of the water is within $1\frac{1}{2}$ inches of the top of the porous cup. Put the zinc in place and set the cell away, without connecting up, for ten or twelve hours, to allow the liquid to thoroughly soak into the porous cup. This action will lower the level of the liquid to about two-thirds the height of the jar, at which level it should be kept, by adding water as it evaporates.

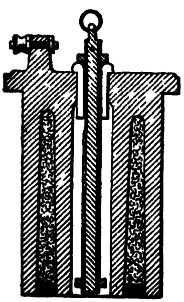


Fig. 54. — Section through Carbon Cylinder Showing MnO_2 Depolarizer.

52. Carbon Cylinder Cell. — Fig. 53 illustrates one type of carbon cylinder cell. In some forms the cylinder is moulded from a mixture of carbon and manganese dioxide, and in others the carbon is made in the form of a porous cup which is filled with oxide of manganese to prevent polarization. Still another form of the same cell is shown in Fig. 54, in which the space between the two concentric carbon cylinders has been filled with oxide of manganese and then sealed in. The zinc rod is prevented from touching the carbon by means of a porcelain insulator. About 4 to 6 ounces of sal-ammoniac are generally used for cells of ordinary size. The salt is placed in the jar, water is poured in until it is about two-thirds full, and then stirred till all the salt is dissolved. When the carbon cylinder is inserted the

solution should be within $1\frac{1}{2}$ inches of the top of the jar. These cells should not be put in warm places, on account of the rapid evaporation of the electrolyte. The E. M. F. is from 1.4 to 1.6 volts for the different forms of this type of cell.

53. Edison-Lalande Cell. — The Edison-Lalande type of cell is a single-fluid cell with a solid depolarizer, but is admirably adapted for use on *closed-circuit work*, as for small motors, electrotyping, telegraphy, etc. Zinc is the positive, and black oxide of copper (CuO) the negative, element. The exciting liquid is a solution of caustic potash. The oxide of copper is obtained by the process of roasting copper turnings, thereafter ground into a fine powder and compressed into solid blocks, from which plates of a suitable size are cut.

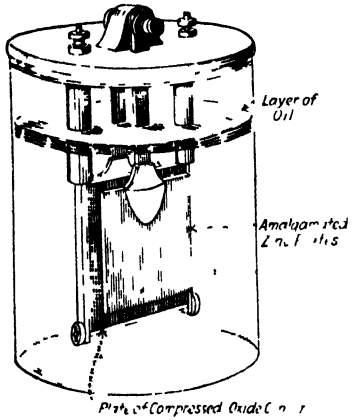


Fig. 55. — Edison-Lalande Cell

Zinc and copper oxide in caustic potash solution

These plates are suspended from the cover of the battery jar (Fig. 55) by a light frame-work of copper, one end of the frame-work terminating as the positive pole of the battery. On each side of the copper oxide element is suspended a zinc plate, which is prevented from coming into contact with the copper oxide plate by means of vulcanite buttons. When the circuit is closed the electrolyte, caustic potash (KOH), is decomposed, the oxygen forming, with the zinc, oxide of zinc, which in turn combines with the electrolyte to form a double salt of zinc and potassium known as potassium zincate (K_2ZnO_2). The potassium liberated by the decomposition of the electrolyte reduces the copper oxide to metallic copper and also forms caustic potash, thus keeping the solution of the same strength. It is important to see that the oxide plates are entirely submerged in the caustic potash solution. Heavy paraffin oil is poured on top of the solution, so as to form a layer about one-quarter inch

deep on the surface, to prevent evaporation. When oil is not used creeping salts are formed and the life of the battery is reduced fully two-thirds. The E. M. F. is low, only 0.7 of a volt, but the internal resistance is also very low, about 0.05 ohm, so that quite a large current can be drawn from the cell.

54. Dry Cells. — Dry cells differ from those already described in that the exciting fluid is combined with some special absorbent, such as sawdust, etc., or is made into a jelly. In the usual type of dry cell the zinc element is in the form of a cylindrical container, which holds the other element (carbon), the depolarizer (manganese dioxide), and the exciting mixture. In one type the mixture or electrolyte has the following proportions by weight: oxide of zinc, 1 part; sal-ammoniac, 1 part; chloride of zinc, 1 part; water, 2 parts. The chemical reactions in this cell are the same as those of the Leclanché cell, ¶ 51. Fig. 56 shows the internal construction of a dry cell. Dry cells, being portable, are very convenient for use where intermittent or small, steady currents are required. The E. M. F. is about 1.4 to 1.6 volts. The most common standard size of dry cell is $2\frac{1}{2}$ inches in diameter and 6 inches high, known as No. 6, but many smaller sizes down to $\frac{8}{16} \times 1\frac{1}{2}$ inches are made for use in pocket flashlights.

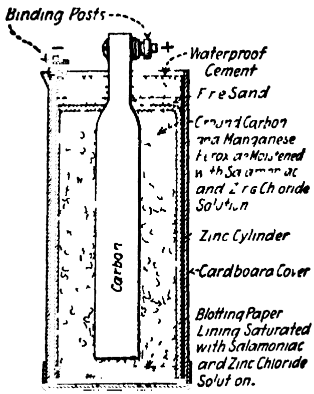


Fig. 56 - Dry Cell, Sectional View

Dry cells are widely used with radio receiving sets which are equipped with vacuum tubes (¶ 386) for rectifying and amplifying the received impulses. Those used for heating the filaments of such tubes are called A batteries, those employed in the plate circuits are called B batteries, and those used in making the grid potential negative are called C batteries. Fig. 57 shows an "Eveready" 1.5-volt A battery, a 45-volt horizontal B battery with intermediate taps, and a 22.5-volt vertical B battery; these have respectively 1, 30 and 15 cells of 1.5 volts each.

55. Classification of Primary Cells. —

Classified by polarization	Open-circuit cells (Grenet, Leclanché). Closed-circuit cells (Daniell, Lalande).
Classified by construction	Single-fluid cells (Grenet, Leclanché, Lalande). Double-fluid cells (Bunsen, Grove, Daniell, Fuller). Dry cells.
Single-fluid cells with	Liquid depolarizer (Grenet). Solid depolarizer (Leclanché, Lalande).

56. Electromotive Force of Some Cells. The E. M. F's which may be expected from voltaic cells in good order when

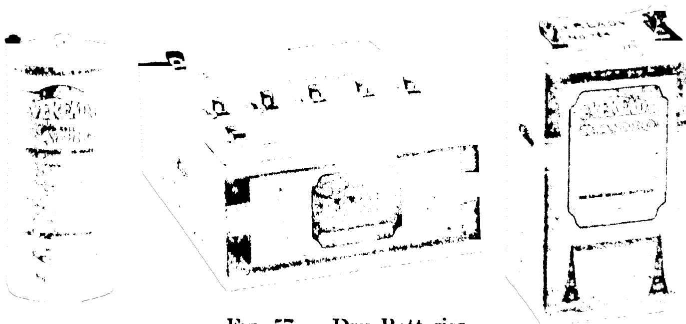


Fig. 57 — Dry Batteries
Used with radio receiving sets

supplied with electrolytes of particular concentration are given below, but the values are subject to some variation.

Bichromate cell. With amalgamated zinc in a solution composed of 12 parts bichromate of potassium to 25 parts sulphuric acid and 100 parts water, and with carbon in a solution of 1 part sulphuric acid to 12 parts water — 2.00 volts.

Bunsen cell. - With amalgamated zinc in a solution composed of 1 part sulphuric acid to 12 parts water, and carbon in fuming nitric acid 1.94 volts. With carbon in nitric acid of density 1.38 the voltage is 1.86.

Daniell cell. — With amalgamated zinc in a solution of 1 part sulphuric acid to 12 parts water, and copper in a saturated solution of copper sulphate — 1.09 volts.

Leclanché cell. — With amalgamated zinc and carbon in a solution of sal-ammoniac, using as depolarizer manganese peroxide with powdered carbon — 1.46 volts.

57. Clark Standard Cell. — A *standard cell* is one which is capable of maintaining a constant E. M. F. for a considerable time; it is therefore used as a standard of potential difference in electrical measurements. A standard cell is not intended to deliver current, in fact high resistances are used with it so that the current drawn from the cell shall be infinitesimal.

The Clark cell was the first form of voltaic cell which could be considered as a standard of E. M. F. It consists of an H-shaped glass vessel with mercury in one leg as the positive and zinc amalgam in the other leg as the negative electrode. Above the mercury is placed as a depolarizer a paste of mercurous sulphate and zinc sulphate, and the electrolyte is a saturated solution of zinc sulphate. The voltage of this cell is 1.433 at 15° C.

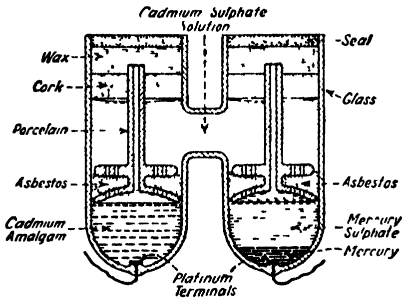


Fig. 58 — Cross Section of Weston Cell.

58. Weston Standard Cell. - The voltage of the Clark cell varies considerably with temperature, and in view of the difficulty of measuring the temperature exactly, the Clark cell has been practically superceded by the Weston standard cell. This cell uses mercury as the positive electrode and an amalgam of 12 per cent cadmium as the negative, and the electrolyte is a saturated solution of cadmium sulphate. It produces an E. M. F. of 1.0183 volts at 20° C.

Fig. 58 shows the construction of the Weston cell; and Fig. 59 illustrates an unsaturated cell for students' use made by the Eppley Laboratory.

59. The Effect of Temperature on Voltage. — The change in voltage of a voltaic cell due to temperature difference is attributed to the thermoelectric force between metals and solutions of their salts. Such forces between two metals have long been recognized and are made use of in thermocouples, ¶ 246. Thermoelectromotive forces between metals and electrolytes have been studied by Carhart; the results show, for example, that with two amalgamated zinc wires in zinc sulphate contained in an experimental cell with its two ends at different temperatures an E. M. F. was developed directed from the cold to the warm end through the liquid. The same is true for copper in copper sulphate. These electromotive forces are small and are respectively 0.76 and 0.69 millivolt per degree C. for a mean temperature of 19° C. In consequence, a Daniell cell having both these combinations will show a thermoelectric power due to heating of the cell as a whole of 0.76 0.69 = 0.07 millivolt per degree C. This voltage variation is of course negligible and is smaller than that due to electrode oxidation.

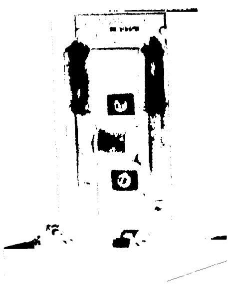


Fig. 59. Unsaturated Standard Cell

While the temperature effect upon voltage is very slight in the Daniell cell, its influence upon the Clark standard cell is quite marked. Heating the mercury leg alone increases the voltage of the cell while heating the zinc leg alone lowers it, Fig. 60. The difference, which is the voltage change obtained by heating the cell as a whole, is given by the slopes of the curves as (6.5 ÷ 24) − (20 ÷ 24) = − 0.56 millivolt per ° C.

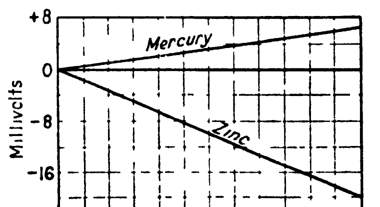


Fig. 60. — Thermoelectric Force Between Electrodes and Electrolyte in Clark Cell.

60. Chemicals for Cells and Their Chemical Symbols. —

Copper Sulphate (blue vitriol), $CuSO_4$

Zinc Sulphate (white vitriol), $ZnSO_4$
Ammonium Chloride (sal-ammoniac), NH_4Cl
Bichromate of Soda, $Na_2Cr_2O_7$
Bichromate of Potassium, $K_2Cr_2O_7$
Chromic Acid, CrO_3
Caustic Potash, KOH
Caustic Soda, $NaOH$
Copper Oxide, CuO
Manganese Dioxide, MnO_2
Mercurous Sulphate, Hg_2SO_4
Cadmium Sulphate, $CdSO_4$
Sulphuric Acid, H_2SO_4
Nitric Acid, HNO_3
Hydrochloric Acid, HCl
Mercuric Chloride, $HgCl_2$
Zinc Chloride, $ZnCl_2$

QUESTIONS

1. Since the hydrogen gas is evolved from the zinc when it is placed in dilute acid, how do you account for the fact that in a voltaic cell, when connected to a circuit, the hydrogen gas is evolved at the copper plate, yet the copper is not attacked by the acid?
2. Upon what does the E. M. F. of a cell depend?
3. Would you expect a very large cell to have the same E. M. F. as a small one of the same kind made up in test tube? Why?
4. Give a list of some materials used in cells, in the order of their potential difference in dilute sulphuric acid.
5. A cell is composed of copper and iron in dilute sulphuric acid. Draw a sketch indicating the + and – plates and electrodes, and the direction of current flow when the plates are connected.
6. What is local action in a cell? How is it prevented?
7. What is the distinction between open- and closed-circuit cells?
8. What are standard cells and for what purpose are they used?
9. Describe a two-fluid cell. Give an example.
10. What is a depolarizer? Give an example of a cell with a solid and a liquid depolarizer, and state how the depolarizer acts in each.
11. Describe the Daniell cell and explain the chemical action.
12. Describe a bichromate cell of the Grenet type.
13. How does the Fuller cell differ from the Grenet cell, since the chemicals and plates used are identical?
14. Describe the Leclanché porous-cup type of cell. How is polarization reduced in this cell?
15. Describe in full the action of the Edison-Lalande cell.
16. Describe the construction of a dry cell.
17. Describe the Weston standard cell.
18. Form a table of all the cells you know of, giving the + and – plates, electrolyte used, depolarizers, name and type (open or closed circuit) in the different columns of the table.

LESSON V

RESISTANCE

61. Resistance. — All bodies offer some opposition to the passage of an electric current through them. Pipes offer opposition to the flow of water through them, due to the friction between the running water and the sides of the pipes.

Electrical *resistance is the opposition offered by any substance to the flow of an electric current through it.* No conducting body possesses perfect conductivity, but every conductor offers some resistance to the passage of a current. All bodies conduct differently, some offering more opposition to the flow of current than others. If the opposition is small, the conductivity is good, and the body is classed as a *conductor.* When the opposition (resistance) is high, the *conductivity* is poor, and the substance is classed as a poor conductor, which ranks it as a good *insulator.* The function of an insulator is to obstruct the flow of current. With a good conductor for conducting current, and a good insulator for confining it to the conductor, we have the practical conditions for handling electricity. The metals and alloys are good conductors.

Resistance is the reciprocal of *conductivity.* The greater the conductivity of a body the less its resistance; the one decreases in the same ratio as the other increases.

62. The Unit of Resistance. — The unit of resistance is called the *ohm,* and is the resistance that would be offered to

the flow of an unvarying electric current by a column of mercury 106.3 centimeters long, weighing 14.4521 grams and having a uniform cross-sectional area, at a temperature of 0° Centigrade (or 32° Fahrenheit). In practice the value of the ohm, corresponding to the above standard, is as follows, *approximately:*

1 ohm = 1000 feet of copper wire $\frac{1}{10}$ inch diameter (No. 10 B. & S.).

1 ohm = 250 feet of copper wire $\frac{1}{20}$ inch diameter (No. 16 B. & S.).

1 ohm = 2 pounds of copper wire $\frac{1}{20}$ inch diameter (No. 16 B. & S.); there are 125 feet per pound.

For wires of the same length the resistance depends upon the size of the wire, for example:

1000 feet of copper wire nearly $\frac{15}{32}$ inch diameter (No. 0000 B. & S.) = 0.04998 ohm.

1000 feet of copper wire $\frac{3}{1000}$ inch diameter (No. 40 B. & S.) = 1070 ohms.

63. The Microhm and Megohm. In calculating or measuring very low resistances one millionth of the value of an ohm is sometimes used and called the *microhm*.

To express a resistance in microhms multiply its value in ohms by 1,000,000, or

$$\text{microhms} = \text{ohms} \times 1{,}000{,}000 \quad \ldots \ldots \quad (1).$$

$$\text{ohms} = \frac{\text{microhms}}{1{,}000{,}000} \quad \ldots \ldots \quad (2).$$

In measuring very high resistances one million ohms are used as the unit and called a *megohm* (often abbreviated meg.).

$$\text{megohms} = \frac{\text{ohms}}{1{,}000{,}000} \quad \ldots \ldots \quad (3).$$

$$\text{ohms} = \text{megohms} \times 1{,}000{,}000 \quad \ldots \ldots \quad (4).$$

Problem 1. — What is the equivalent resistance in megohms of 47,500,000 ohms?

By Formula (3) $\frac{47{,}500{,}000}{1{,}000{,}000} = 47.5$ megohms.

Problem 2. — Give the equivalent resistance in microhms of 0.00385 ohm.

By Formula (1) $0.00385 \times 1{,}000{,}000 = 3850$ microhms.

Problem 3. — What is the equivalent resistance in ohms of 225 microhms?

By Formula (2) $$\frac{225}{1{,}000{,}000} = 0.000225 \text{ ohm.}$$

64. Conductors and Insulators. — In the following table the substances are arranged in the order of their *conductance*, the best conductors being at the top, and the best insulators at the bottom, of the list. Any substance in the table is approximately a *better conductor* than any substance which *follows* it; thus, lead is a better conductor than mercury, but not so good as zinc. A slight variation in the quality of a substance would change its position in the list with reference to some other substance; for example, some marble is useless for switchboards on account of metallic veins running through it. The same is true of slate, so that the position of these substances on the list is approximate.

Table III. Conductors and Insulators

Good Conductors (metals and alloys)	Silver
	Copper
	Aluminum
	Zinc
	Brass (according to composition)
	Platinum
	Iron
	Nickel
	Tin
	Lead
	German silver (copper 2 parts, zinc 1, nickel 1)
	Platinoid (German silver 49 parts, tungsten 1)
	Antimony
	Mercury
	Bismuth
	Manganin (copper 14 parts, ferromanganese 5, nickel 1)
	Nichrome (nickel and chromium)
Fair Conductors	Charcoal and coke
	Carbon
	Plumbago
	Acid solutions
	Sea water
	Saline solutions
	Metallic ores
	Living vegetable substances
	Moist earth

Partial Conductors

- Water
- The body
- Flame
- Linen and cotton
- Dry woods: mahogany, pine, rosewood, teak, etc.
- Marble

Nonconductors or Insulators

- Slate
- Oils
- Porcelain
- Dry leather and paper
- Wool and silk
- Sealing wax
- Sulphur and resin
- Gutta percha
- Shellac
- Ebonite
- Mica
- Paraffin wax
- Glass (varies with quality)
- Dry air.

65. Wire Measure. — The Circular Mil. — In calculating the resistance of *round* wires for electrical purposes, a *circular* measure is used to express the cross-sectional area of the wire, since it is more convenient than the old method of measuring the area of circles in *square inches;* and a *circular unit* of area, the *circular mil,* is used instead of a square unit of area. One circular mil is the area of a circle whose diameter is one mil. The term *mil* means one one-thousandth of an inch ($\frac{1}{1000}$ or 0.001 inch = 1 mil).

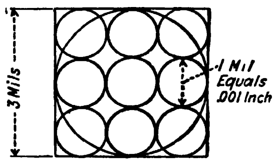


Fig. 61. — Diagram Illustrating Circular Mil Areas.

Area of large circle equals the area of the nine small circles.

If the diameter of a wire measures 2 mils ($\frac{2}{1000}$ or 0.002 inch), then it has a sectional area of 4 circular mils, the area being obtained by expressing the diameter of the wire in mils and squaring it (multiplying it by itself). The square of any diameter, expressed in thousandths of an inch, will give as a product the number of circular units that can be placed side by side in a square the sides of which are equal to the diameter that has been squared; the sum of the areas of

the small circles contained within such a square equals the area of the large circle. This is illustrated in Fig. 61, where the area of the large circle equals the sum of the areas of the nine small circles. This is evident from the following: If we take the diameters of the small circles as unity, then the diameter of the large circle is three. The area of each of the small circles equals $\frac{\pi}{4} = 0.7854$ (that is $1^2 \times 0.7854$); the sum of the areas of the small circles equals 7.0686 (that is 9×0.7854); the area of the large circle equals $3^2 \times 0.7854 = 9 \times 0.7854 = 7.0686$. Therefore, since the area of the large circle equals the sum of the areas of the small circles, the area of a wire in circular mils is equal to *the square of the diameter expressed in mils.*

FIRST: TO FIND THE CIRCULAR MIL AREA OF ANY ROUND WIRE WHEN ITS DIAMETER IN INCHES IS KNOWN:

Express the diameter in mils and square it.

Let d = diameter in mils,
d^2 = diameter squared,
C. M. = circular mil area.

Then,

$$C.\,M. = d^2 \quad \text{(5)}.$$

Problem 4. — What is the circular mil area of a wire $\frac{1}{4}$ inch in diameter?

Since 1 inch = 1000 mils, $\frac{1}{4}$ inch $= \frac{250}{1000}$ or 250 mils.

By Formula (5) C. M. $= d^2 = d \times d = 250 \times 250 = 62{,}500$ C. M.

SECOND: TO FIND THE DIAMETER OF ANY WIRE WHEN THE CIRCULAR MIL AREA IS KNOWN:

Extract the square root of the circular mil area. The result is the diameter expressed in mils, or

$$d = \sqrt{C.\,M.} \quad \text{(6)}.$$

Problem 5. — What is the diameter of a wire if the area is 6530 C. M. (No. 12 B. & S.)?

By Formula (6) $d = \sqrt{C.\,M.} = \sqrt{6530} = 81$ mils nearly, or 0.081 inch diameter.

66. The Square Mil. — Many electrical conductors, such as bus-bars, copper ribbon, etc., are square or rectangular in

cross-sectional area, and in computing areas of such conductors the square measure is used, for which the units are the square mil and the square inch, one *square mil* being the area of a *square* whose sides measure one mil or one one-thousandth of an inch. One square mil equals 0.000001 square inch. It is sometimes necessary to find the equivalent area in round wire measure of conductors of rectangular cross section; the relations used in this connection are: one square mil equals 1.2732 circular mils, and one circular mil equals 0.7854 square mil.

THIRD: TO FIND THE AREA OF A RECTANGULAR WIRE IN SQUARE MILS:

Express the dimensions in mils and find the product of the dimensions. The result is the area in square mils.

Let c = thickness in mils,
d = width in mils.

$$\text{Sq. mils} = c \times d \quad \ldots\ldots\ldots\ldots \quad (7).$$

Problem 6. — A copper ribbon for a field coil measures $\frac{5}{8}$ inch × $\frac{1}{8}$ inch. Find its square mil area.

$\frac{5}{8}$ = 0.625 inch, or 625 mils; $\frac{1}{8}$ = 0.125 inch, or 125 mils.

By Formula (7) Sq. mils = c × d = 125 × 625 = 78,125 sq. mils.

FOURTH: TO CONVERT CIRCULAR MIL AREA INTO SQUARE MIL AREA:

Multiply the circular mil area by 0.7854. The result will be in square mils.

Since one circular mil = 0.7854 square mil, therefore,

$$\text{sq. mils} = \text{C. M.} \times 0.7854 \quad \ldots\ldots\ldots \quad (8).$$

Problem 7. — What is the square mil area of a wire $\frac{1}{4}$ inch in diameter? In Problem 4 the area was calculated to be 62,500 C. M.

By Formula (8) Sq. mil area = C. M. × 0.7854 = 62,500 × 0.7854 = 49,087 sq. mils.

FIFTH: TO CONVERT SQUARE MIL AREA INTO CIRCULAR MIL AREA:

Multiply the square mil area by 1.2732. The result will be in circular mils.

Since one square mil = 1.2732 mils, it follows that

$$\text{C. M.} = \text{sq. mils} \times 1.2732 \quad \ldots\ldots\ldots \quad (9).$$

Problem 8. — Find the circular mil area of the copper wire in Problem 6.

In Problem 6 the square mil area = 78,125.

By Formula (9) C. M. = sq. mils $\times$ 1.2732 = 78,125 $\times$ 1.2732 = 99,468 C. M.

67. Laws of Resistance. —

I. *It is the cross-sectional area of a material which conducts and not its surface.* This can be proved by using a wire tube in comparison with a solid wire of the same outside diameter (Law I, Fig. 62).

II. *The resistance of a conductor is directly proportional to its length.* Thus, 2000 feet of copper wire 0.1 inch diameter will have 2 ohms resistance; 10,000 feet, 10 ohms, etc. (Law II, Fig. 62).

III. *The resistance of a conductor is inversely proportional to its cross-sectional area, and in the case of round wire inversely proportional to the square of the diameter.* The area of a round wire varies directly as the diameter squared, or area varies as d^2. A wire one half inch in diameter has four times as great a resistance as a wire one inch in diameter, because the area is one quarter as large. Again: No. 24 (B. & S.) wire has a diameter of 0.02 inch and No. 30 has a diameter of 0.01 inch, or one half the diameter of No. 24; 38 feet of No. 24 have a resistance of one ohm, and 9.5 feet of No. 30 have a resistance of one ohm; this agrees with the foregoing statements since $\frac{38}{2^2} = \frac{38}{4} = 9.5$ (Law III, Fig. 62).

IV. *The resistance of a conductor of given length and cross section depends upon the material of which it is made.* For example, the resistance of 1000 feet of copper wire $\frac{1}{10}$ inch diameter (No. 10 B. & S.) is about 1 ohm, while the resistance of a piece of iron wire of the same length and cross section is about 6 ohms, and a similar piece of German silver about 12 ohms (Law IV, Fig. 62).

V. *The resistance of a conductor depends upon the temperature and is affected by any other cause which modifies its molecular condition.* If copper, German silver, and platinoid are heated the resistance of the copper is increased nearly 10 times as much as that of the German silver, and 20 times as much as platinoid (Law V, Fig. 62).

All metals have their resistance increased by an increase of temperature. Carbon and all electrolytic conductors (battery

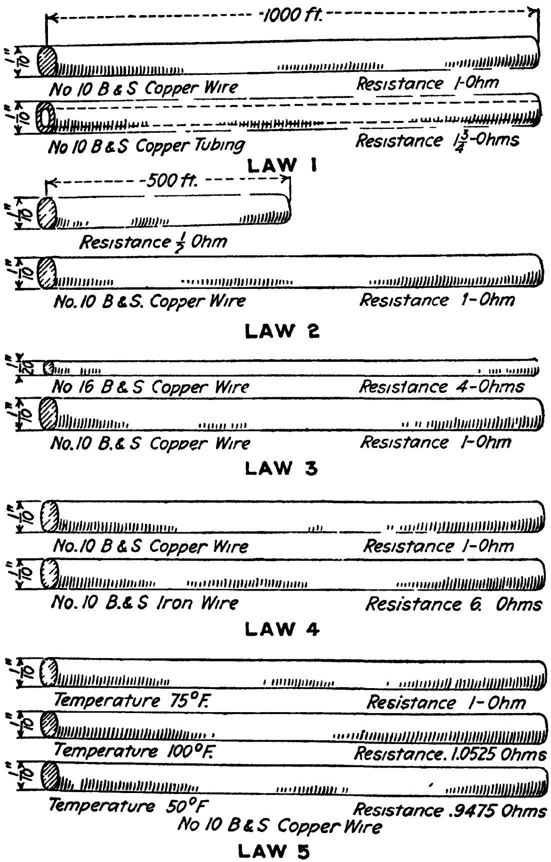


Fig. 62. — Laws of Resistance for Electrical Conductors.

solutions) decrease in resistance as the temperature increases. The resistance of copper increases about one quarter of one per cent (0.0023) for each degree temperature rise, *Fahrenheit*

scale. See ¶ 241. The *hot* resistance of the carbonized filament of an incandescent lamp is about one half the *cold* resistance. The Mazda tungsten filament lamp is just the opposite; its filament has a higher resistance while incandescent than when cold.

The following experiments will verify the above laws. The resistances used in these experiments consists of four spools of wire, as follows: spool No. 1 contains 25 feet of No. 24 B. & S. copper wire, diameter 20.1 mils; spool No. 2, 50 feet of No. 24

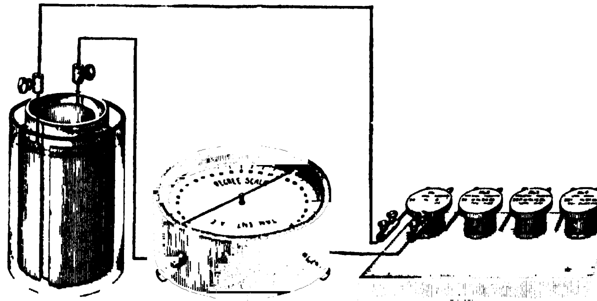


Fig. 63. — Connections of Apparatus for Verifying Laws of Resistance. (See Experiments 23 to 27).

B. & S. copper wire; spool No. 3, 25 feet of No. 18 B. & S. copper wire, diameter 40.3 mils; spool No. 4, 25 feet of No. 24 B. & S. *German silver* wire.

Experiment 23. — Connect spool No 1, of the resistance spool set, to a Student's Daniell cell, with the detector galvanometer (Fig. 172) in the circuit, as shown in Fig. 63, and note deflection of the needle.

Experiment 24. — Connect spool No 2 in place of No 1, and note that the deflection is smaller than before. Why? (Law II)

Experiment 25. — Connect spool No. 3 in place of No. 2, and note deflection. It is greater than was obtained with either Nos. 1 or 2. Why is this so, since its wire is of the same length and material as No. 1? (Law III.)

Experiment 26. — Substitute spool No. 4 for No. 3; note deflection. This deflection is smaller than in any of the other cases. The wire on spool No. 4 is of exactly the same length and cross-sectional area as that on spool No. 1. Why is the deflection so much smaller? (Law IV.)

Experiment 27. — Connect several bichromate cells in series and to spool No. 4, passing a current through it for a short time. The spool be-

comes warm. Now connect it again in the same circuit as in Experiment 26, and note that the deflection is smaller than before. Why is this so, since it is exactly the same spool as was used in Experiment 26? (Law V.)

68. Calculation of Resistance. — In calculating the resistance of metal conductors, the resistance of a *mil-foot* of the metal is taken as a constant (K), and used in computing the resistance of a wire of correspondingly greater length and area than the mil-foot. The *mil-foot* is used as a unit wire having a cross-sectional area of one circular mil and measuring one foot in length. The resistance per mil-foot (K) is sometimes called the *resistivity* or *specific resistance* of a material, and varies with different materials. See ¶ 70.

One foot of copper wire $\frac{1}{1000}$ inch in diameter has a resistance of 10.79 ohms (K) at 75° Fahrenheit. Ten feet will have 107.9 ohms. One foot of copper wire $\frac{2}{1000}$ inch in diameter will have one fourth the resistance or 10.79 divided by 4 = 2.69 ohms. If this last wire were iron, it would have 6 times the resistance, or 16.14 ohms. *Resistance varies directly as the length, inversely as the cross-sectional area, and with the material of the conductor.*

GIVEN THE LENGTH AND AREA OF ANY WIRE TO FIND ITS RESISTANCE:

The resistance of any wire is equal to its length in feet multiplied by the resistance of a mil-foot (K) *and this product divided by its area in circular mils.*

Let L = length of the wire in feet,
R = resistance in ohms,
C. M. = circular mil area,
K = resistance of one mil-foot in ohms.

Then,
$$R = \frac{K \times L}{C.M.} \quad \text{(10)}.$$

Problem 9. — Find the resistance of 1000 feet of copper wire having a cross-sectional area of 10,000 C. M.

Since K for copper = 10.79, L = 1000 feet, C.M. = 10,000, it follows from Formula (10) that $R = \frac{K \times L}{C.M.} = \frac{10.79 \times 1000}{10,000} = 1.079$ ohms.

The value of K is constant for the same wire, but different for each metal, and for copper at 75° Fahrenheit it is 10.79 ohms.

The value of K for other metals can be taken from the table below, and the resistance of any wire can be calculated when its dimensions are known. The resistance obtained corresponds with the temperature for which K is given. The following table gives the resistance of a foot of wire 0.001 inch in diameter, or the values of K, for different metals when the temperature is 68° Fahrenheit (see ¶ 241). K therefore is the resistance of 1 mil-foot.

Table IV. Resistances of a Mil-foot of Metals (Values of K)

Silver, 9.81	Zinc, 36.69	German silver, 128.29
[1] Copper, 10.79	Platinum, 59.02	[3]Platinoid, 188.93
[2] Aluminum, 17.21	Iron, 63.35	Mercury, 586.24

Problem 10. — Substitute an iron wire for the copper wire in Problem 9, and find its resistance.

By Formula (10) $R = \frac{K \times L}{C.M.} = \frac{63.35 \times 1000}{10,000} = 6.335$ ohms,

where K for iron = 63.35.

Iron has thus about six times the resistance of copper.

69. Wire Calculations. —

CASE 1. — GIVEN THE RESISTANCE AND AREA OF A WIRE TO FIND ITS LENGTH:

The length of any wire is equal to its resistance multiplied by its circular mil area, and this product divided by the resistance of a mil-foot (K).

$$L = \frac{R \times C.M.}{K} \quad \ldots\ldots \quad \textbf{(11)}.$$

Problem 11. — What is the length of German silver wire wound on a resistance spool, if its resistance is 500 ohms and the size of wire is No. 20 B. & S.?

No. 20 B. & S. = 1022 C. M. (from Table VI). K for German silver = 128.29 (from Table IV).

By Formula (11) $L = \frac{R \times C.M.}{K} = \frac{500 \times 1022}{128.29} = 3983$ feet.

[1] 10.79, or (10.8) is generally used in practice as the value of K for *commercial* copper at the average working temperature of 75° Fahrenheit.

[2] Value for annealed aluminum (conductivity = 62 % that of copper).

[3] German silver 49 parts, tungsten 1 part.

CASE 2. — GIVEN THE LENGTH AND RESISTANCE OF A WIRE TO FIND THE AREA:

The area in circular mils of any wire is equal to its length multiplied by the resistance of a mil-foot (K) *and this product divided by its resistance.*

$$C.\,M. = \frac{L \times K}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (\mathbf{12}).$$

Problem 12. — What is the circular mil area of 1000 feet of a certain iron wire, if its resistance is 30 ohms?

K for iron 63.35 from Table IV.

By Formula (12) $C.\,M. = \frac{L \times K}{R} \quad \frac{1000 \times 63.35}{30} = 2111.6$ C. M.

CASE 3. — GIVEN THE AREA OF A WIRE TO FIND THE WEIGHT.

The weight per mile (5280 feet) *of any bare copper wire in pounds is equal to the area in circular mils divided by the constant 62.5.* Copper weighs about 555 pounds per cubic foot; iron weighs about 480 pounds per cubic foot.

$$\text{Pounds per mile (bare copper wire)} = \frac{C.\,M.}{62.5} \quad . \quad . \quad . \quad . \quad . \quad (\mathbf{13}).$$

$$\text{Pounds per foot (bare copper wire)} = \frac{C.\,M.}{62.5 \times 5280} \quad . \quad . \quad (\mathbf{14}).$$

$$\text{Pounds per mile (bare iron wire)} = \frac{C.\,M.}{72.13} \quad . \quad . \quad . \quad . \quad . \quad (\mathbf{15}).$$

Problem 13. — The circular mil area of a No. 10 B. & S. wire is 10,380. How many pounds of bare copper wire will be required for two lines running a distance of 5 miles?

By Formula (13) lbs. per mile $= \frac{C.\,M.}{62.5} = \frac{10{,}380}{62.5} = 166.08$ lbs. per mile.

Therefore the total weight is $166.08 \times 5 \times 2 = 1660.8$ lbs.

70. Specific Resistance, Relative Resistance and Conductivity of Metals. — In comparing different materials, some standard of unit dimensions must be adopted. The commercial copper wire standard generally used is the Annealed Copper Standard (page 67), recommended by the United States Bureau of Standards, having a specific resistance

of 1.7241 microhms per cubic centimeter at a temperature of 20° Centigrade. In scientific writings, *specific resistance* is usually given as the resistance between two opposite faces of a cube of the material at 0° Centigrade, instead of on the basis of a wire one foot long and one mil in diameter, which is generally used in practice. The following table (Table V) gives the specific resistance for a centimeter cube and an inch cube of the materials, also the relative resistance and conductivity. Silver, the best conductor, has a conductivity of 100%.

Table V. Specific Resistance, Relative Resistance, and Conductivity of Conductors

Metals	Resistance in Microhms at 0° Centigrade		Relative Resistance	Relative Conductivity
	Centimeter Cube	Inch Cube		
Silver (annealed)	1.521	0.598	1.000	100
Copper (annealed)	1.639	0.645	1.075	93
Copper (hard drawn)	1.670	0.667	1.096	91
Aluminum (annealed)	2.76	1.186	1.81	55
Zinc	5.87	2.310	3.86	26
Platinum	9.04	3.555	5.93	16.8
Iron	9.70	3.814	6.37	15.7
Lead	19.60	7.706	12.90	7.7
German silver	20.65	8.127	13.6	7.4
Mercury	96.14	37.825	63.2	1.6

71. The Wire Gage.—A number of wire gages, differing slightly from each other, have been originated by different manufacturers of wire, but the one generally used in this country is the B. & S. gage (Brown & Sharpe Manufacturing Co.), commonly called the *American Wire Gage.* Tables of several other gages will be found in the Appendix. Table VI gives the B. & S. gage. The first column gives the gage number; for example, the scale in the B. & S. gage is from No. 0000 (four naughts) wire (460 mils diam.) to No. 40 (3 mils diam.), the sizes decreasing as the gage numbers increase. The diameter, area, weight, length, and resistance are also given for each size wire.

Table VI. Wire Table, Standard Annealed Copper at a Temperature of 25° Centigrade (77° Fahrenheit)

American Wire Gage (Brown & Sharpe)

Gage No	Diam in Mils d	Area	Weight		Length		Resistance	
		Cir Mils d²	Lbs per 1000 ft	Lbs per ohm	Feet per lb	Feet per ohm	Ohms per 1000 ft	Ohms per lb
0000	460 0	211660	640 5	12810	1 561	20010	0 04998	0 00007805
000	409 6	167800	507 9	8057	1 968	15870	06303	0001217
00	364 8	133100	402 8	5067	2 482	1[illegible]80	07947	0001935
0	324 9	105500	319 5	3187	3 130	9979	.1002	0003138
1	289 3	83690	253 3	2004	3 947	7913	.1264	0004990
2	257 6	66370	200 9	1260	4 977	6276	.1594	0007934
3	229 4	52640	159 3	792 7	6 276	4977	.2009	001262
4	204 3	41740	126 4	498 6	7 914	3947	.2534	002006
5	181 9	33100	100 2	313 5	9 980	3130	.3195	003189
6	162 0	26250	79 46	197 2	12 58	2482	4029	005071
7	144 3	20820	63 02	124 0	15 87	1968	5080	008064
8	128 5	16510	49 98	77 99	20 01	1561	6406	01282
9	114 4	13090	39 63	49 05	25 23	1238	8078	02039
10	101 9	10380	31 43	30 85	31 82	981 8	1 019	03242
11	90 74	8234	24 92	19 40	40 12	778 5	1 284	05155
12	80 81	6530	19 77	12 20	50 59	617 4	1 620	08196
13	71 96	5178	15 68	7 673	63 80	489 6	2 042	1303
14	64 08	4107	12 43	4 826	80 44	388 3	2 576	2072
15	57 07	3257	9 858	3 035	101 4	307 9	3 248	3295
16	50 82	2583	7 818	1 909	127 9	244 2	4 095	5239
17	45 26	2048	6 200	1 200	161 3	193 7	5 164	8330
18	40 30	1624	4 917	0 7549	203 4	153 6	6 512	1 325
19	35 89	1288	3 899	4748	256 5	121 8	8 210	2 106
20	31 96	1022	3 092	2986	323 4	96 59	10 35	3 349
21	28 46	810 1	2 452	1878	407 8	76 60	13 06	5 325
22	25 35	642 4	1 945	1181	514 2	60 74	16 46	8 467
23	22 57	509 5	1 542	07427	648 4	48 17	20 76	13 46
24	20 10	404 0	1 223	04671	817 7	38 20	26 18	21 41
25	17 90	320 4	0 9699	02938	1031	30 30	33 01	34 04
26	15 94	254 1	7692	01847	1300	24 02	41 62	54 13
27	14 20	201 5	6100	01162	1639	19 05	52 48	86 07
28	12 64	159 8	4837	007307	2067	15 11	66 18	136 8
29	11 26	126 7	3836	004595	2607	11 98	83 46	217 6
30	10 03	100 5	3042	002890	3287	9 503	105 2	346 0
31	8 928	79 70	2413	001818	4145	7 536	132 7	550 2
32	7 950	63 21	1913	001143	5227	5 976	167 3	874 8
33	7 080	50 13	1517	0007189	6591	4.739	211 0	1391
34	6 305	39 75	.1203	0004521	8310	3 759	266 1	2212
35	5 615	31 52	09542	0002843	10480	2 981	335 5	3517
36	5 000	25 00	07568	0001788	13210	2 364	423 0	5592
37	4 453	19 83	06001	0001125	16660	1 874	533 5	8892.
38	3 965	15 72	04759	00007074	21010	1 487	672 7	14140
39	3 531	12 47	03774	00004448	26500	1 179	848 2	22480
40	3 145	9 888	02993	00002798	33410	0 9349	1070	35740

The *fundamental resistivity* used in calculating this table is the Annealed Copper Standard of the United States "Bureau of Standards," and is 0.15328 ohm (meter, gram) at 20° Centigrade. The *temperature coefficient* for this particular resistivity is at 20° Centigrade = 0.00393, or at 0° = 0.00427. Specific Gravity = 8.89.

This table is intended as an ultimate reference table and is computed to a greater precision than is desired in practice.

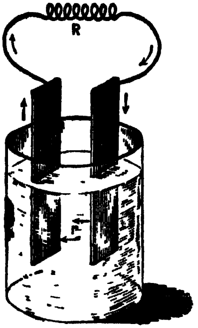


Fig. 64. – The Internal and External Resistance of a Cell.

It will be observed in the table that the cross-sectional areas of wires increase to double value in lowering the gage size by three numbers. The ratio of the areas for two successive gage numbers is 1.26. The weights of wires vary in the same ratio and their resistances vary in the inverse ratio.

72. Internal Resistance of a Battery. — Resistance in a voltaic circuit may be divided into two parts: *internal resistance* (r), which the current encounters in passing through the liquid from one plate to the other, and *external resistance* (R), or that of the outer circuit (see Fig. 64). The current that a cell will give, therefore, depends upon its internal resistance, and will be greater the less this resistance, and *vice versa*. The internal resistance is governed by the same laws as the external resistance. Thus:

$$r \text{ (internal resistance)} = K \times \frac{\text{distance between plates}}{\text{areas of plates submerged}}$$

where the constant K depends upon the electrolyte used.

73. Rheostats. — The usual method of regulating and controlling the current required for various electrical purposes is by inserting, or taking out of a circuit, resistance. An adjustable resistance or any apparatus for changing the resistance without opening the circuit is called a *rheostat*. The function of a rheostat is to absorb electrical energy, and this energy, which appears as heat, is wasted instead of performing any useful work. A rheostat may be constructed of coils of iron wire, iron plates or strips; of carbon, either pulverized in tubes or in the form of solid rods or disks; German silver,

platinoid, or wires of other alloys wound on spools; columns of liquids, as water and mercury, etc. The cross-sectional area of the material must be sufficient to carry the current without excessive heating. In rheostats used for regulating the current in commercial electric circuits no great degree of accuracy of the resistance coils is required, as is the case in laboratory rheostats (¶ 75).

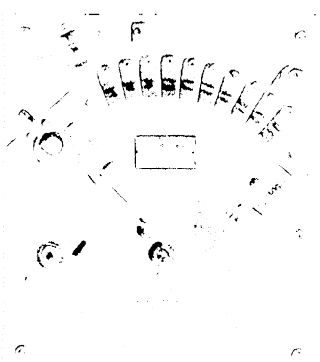


Fig. 65. — One Type of Rheostat. Ward-Leonard starting box for starting motors.

Fig. 65 illustrates a commercial type of rheostat, in which the various coils are connected to brass buttons or contact segments. By moving a metallic connecting arm over the segments from left to right, the coils are successively thrown out of circuit and the resistance is lowered. Such rheostats are used in starting direct-current motors, the general plan of connections being shown in Fig. 66. The rheostat arm is provided with a spring which returns it to the *off* position if the handle is released during the starting of the motor. After the motor has been brought up to speed by moving the arm to the extreme right or *on* position, the low-voltage release magnet holds the arm in that position, see ¶317.

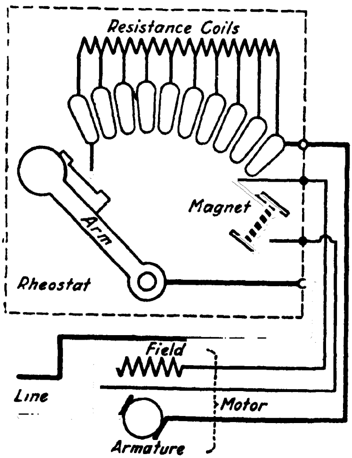


Fig. 66.—Connections of a Rheostat.

74. Resistance of Connections. — When two surfaces are pressed *lightly* together the resistance of the contact is much

greater than if the surfaces of contact are *firmly* pressed together. For this reason all binding screw contacts should be thoroughly cleaned to a bright metallic lustre when used, and screwed down so as to clasp the wires firmly. All joints in electrical conducting systems should be soldered to decrease the resistance of contact.

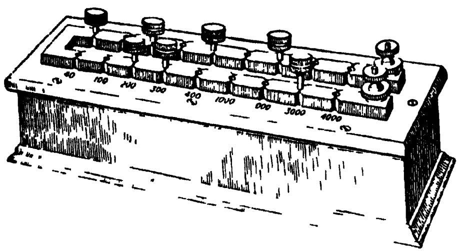


Fig. 67. — Laboratory Type of Rheostat.

75. Laboratory Rheostats. — For making electrical measurements accurately standardized resistance boxes are required. The current passed through these rheostats is generally very small so that the resistance wire, generally an alloy such as German silver, platinoid, or manganin, is small in size and is wound on spools which are contained in a case, as shown in Fig. 67. Brass strips are mounted on the top of the case, and the terminals of each coil connected to two adjacent strips as shown in detail in Fig. 68. The insertion of a tapered metal plug into a tapered hole formed by the adjacent strips, short-circuits or cuts out the resistance coil. By removing the plugs, resistance is inserted in the circuit in which the box is connected. The resistance value of each coil is stamped on the box, as shown in Fig. 67, so that the resistance in circuit is found by the addition of the values of the coils unplugged. The coils are wound *noninductively*, ¶ 269, and the size of the wire used must be such that no appreciable error will be introduced by the heating of the coils.

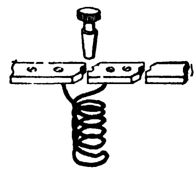


Fig. 68. — Connection of a Resistance Coil in Laboratory Rheostats.

QUESTIONS

1. The conductivity of a porcelain rod is very low. How will this affect its insulating qualities?

2. What is the function of an insulator?

3. The resistance of 5 pounds of No. 36 platinoid wire is very high. How does this affect the conductivity?

4. A battery sends a certain current through a piece of copper wire Would the same cell send more or less current through another piece of copper wire twice as long but of double the area of the first piece?

5. If the second wire in Question 4 was twice the length and twice the diameter of the first wire, what would be your answer?

6. Current from a cell flowing through a piece of iron wire deflects a galvanometer needle 40 degrees. When a piece of aluminum of similar dimensions to that of the iron is substituted, the deflection is 55 degrees. How do you account for this, since both wires are exactly the same size?

7. One mile of a certain iron wire has a resistance of 6 ohms. What will be the resistance of one-quarter of a mile of the same wire?

8. What is the function of a rheostat? How is its resistance varied?

9. What advantage does an enamel type of rheostat possess over one constructed in the form of coils?

10. State what is meant by specific resistance?

PROBLEMS

1. The insulation of a wire measures 16.75 megs. What is its equivalent resistance in ohms? *Ans.* 16,750,000 ohms.

2. What is the circular mil area of a wire $\frac{3}{16}$ inch in diameter? *Ans.* 35,156 C. M.

3. The circular mil area of a wire is 5625. What is its diameter? *Ans.* 75 mils.

4. An armature is wound with copper bars $\frac{3}{16}$ by $\frac{3}{8}$ of an inch. What is their equivalent area in circular mils? *Ans.* 89,522 C. M.

5. The resistance of the series coil of a dynamo is 0.0065 ohm. Express its resistance in microhms. *Ans.* 6500 microhms.

6. What is the square mil area of a No. 12 B. & S. copper wire? *Ans.* 5128 sq. mils.

7. What is the resistance of 5 pounds of No. 18 B. & S. copper wire, allowing 5 per cent of its weight for insulation? *Ans.* 6.294 ohms.

8. The coils of a rheostat, constructed of No. 8 B. & S. iron wire, have a resistance of 10 ohms. What length of wire was required? *Ans.* 2606 feet.

9. A rectangular wire has a square mil area of 20,616. What is the equivalent circular mil area? *Ans.* 26,249 C. M.

10. What size of B. & S. wire has an equivalent area to the wire in Problem 9? *Ans.* No. 6.

11. Calculate the resistance of 2000 feet of No. 6 B. & S. copper wire. *Ans.* 0.822 ohms.

12. Construct from your *own calculations,* a wire table for No. 12 B. & S. copper wire, giving the circular mil area, square mil area, pounds per mile, pounds per foot, pounds per ohm, feet per pound, feet per ohm, ohms per pound, and ohms per foot.

LESSON VI

EFFECTS PRODUCED BY THE ELECTRIC CURRENT

Effects of the Current — Heating Effect — Magnetic Effect — Chemical Effect — Electrolysis — Electrolysis of Copper Sulphate — Electrolysis of Zinc Sulphate — Electrolysis of Lead Acetate — Electroplating — Electrotyping — Polarity Indicator — Questions

76. Effects of the Current. — A current of electricity is believed to be a transfer of electrons through a circuit, ¶ 25; and since these carriers are so minute, a direct measurement of them is impractical. Consequently, *an electric current is measured by the effects it produces, all of which are commercially utilized.* The effects manifested by a current of electricity are: *Heating Effect*, *Magnetic Effect*, *Chemical Effect*, and *Physiological Effect.* The first three of these effects are treated in this book. A current passed through the body produces muscular contractions, which are said to be due to the physiological effect. Electrotherapeutics deals with the study of this effect.

By a *direct* or *continuous current* is meant one which flows always in the same direction, as, for example, the current from a battery or direct-current generator. In a *pulsating current* the direction is uniform, but the current strength varies. Most direct-current generators furnish a pulsating current, but the pulsations are so small that the current becomes practically constant. In an *alternating current* the direction is reversed at short intervals, and the current strength also varies periodically.[1] Such currents are furnished by alternating-current generators, usually called *alternators.*

77. Heating Effect. —

Experiment 28. — Connect the terminals of a bichromate cell to a piece of No. 32 iron wire about one inch long. The wire becomes so hot that it is luminous, thus illustrating the *heating* effect of a current of electricity.

[1] In most of the following pages the references to current strength are true for direct currents. and exceptions must be made if other currents are considered.

The chemical energy inside of the cell is thus converted into electrical energy outside of the cell in the form of heat and light. If the current is strong enough the wire will be melted.

Experiment 29. — Substitute for the iron wire in Experiment 28 a piece of copper wire of the same size and length. A smaller change of temperature will be noted.

Experiment 30. — Close the circuit of the cell without any fine wire in the circuit. More heat is now generated inside of the cell than in the external conducting wires.

Every wire which conducts a current of electricity becomes heated to some extent as a result of the current, because the best conductors offer some opposition (resistance) to the flow of the current, and it is in overcoming this resistance that the heat is developed. If the wire is large in cross-sectional area and the current small, the heat developed will be so small in amount as not to be recognized by the touch, yet, nevertheless, some heat is evolved from the wire; upon the other hand, with a small wire and a large current it becomes quite hot. As the heat increases with the resistance of the conductor used, by employing a poor conductor we obtain both light and heat. This principle is used in the incandescent electric lamp, in which a high-resistance solid conductor called the filament is inclosed in a glass bulb from which the air has been exhausted, thereby preventing combustion of the filament. The current is passed through the filament and heats it to a state of incandescence. Fig. 69 depicts a carbon filament lamp. Of the electric energy expended in this type of lamp, only about 5 per cent is represented by the light emitted, while the balance appears as heat, so that such a lamp, while convenient, is not an efficient source of illumination. The heating effect of the current is also utilized in the various electric cooking utensils on the market, in electric welding, electric smelting, and in reducing metals from their ores.

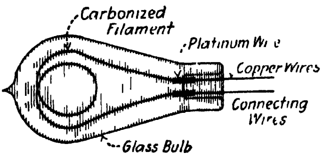


Fig. 69. — Electric Incandescent Lamp.

78. Magnetic Effect. — A wire carrying a current of electricity deflects a magnetic needle. When insulated and coiled

around an iron core the current magnetizes the core. If the current flowing through a wire be sufficiently strong, the wire will attract iron filings, proving the existence of the magnetic field around the wire. This effect is very important and is treated under Electromagnetism, Lesson XIII.

79. Chemical Effect. — We have noted in a simple voltaic cell (¶ 36) how electrolytic decomposition takes place inside the cell when a current is flowing. The current is also capable of decomposing certain chemical compounds (liquids) outside of the cell, when it is passed through them, breaking up the compounds into their constituent parts. Liquids may be divided into three classes: (1) *Those which do not conduct electricity at all*, such as many of the oils, particularly petroleum; (2) *liquids which conduct without decomposition*, as mercury and molten metals, which conduct just as solids; (3) *liquids which are decomposed when they conduct a current*, as the dilute acids, solutions of metallic salts and some fused compounds.

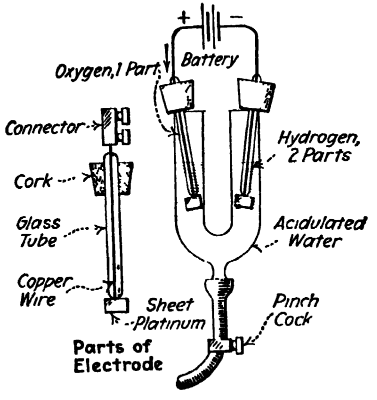


Fig. 70. — Glass U-Tube with Electrodes Forming an Electrolytic Cell.

Experiment 31. Electrolysis of Water. — Fill the U-tube (Fig. 70) with water, and add a few drops of sulphuric acid to make the liquid a better conductor. Connect the terminals of two bichromate cells joined in series (¶ 115) to the two platinum terminals shown in the U-tube, so that the circuit from the cells will be completed through the acidulated water. Have the corks quite loose in the U-tube for the gases to escape. When the circuit is completed bubbles of gas immediately rise from both platinum plates, more, however, from the platinum plate connected with the negative pole of the battery. The gases may be collected *separately* by the forms of apparatus shown in Figs. 73 and 76, or collected *together* in one tube in the form shown in Fig. 74.

During this electrochemical action the current decomposes the water, liberating hydrogen gas at the negative battery

pole and oxygen gas at the positive battery pole. Twice as much hydrogen as oxygen gas is liberated. Water is composed of these two gases, hydrogen and oxygen, in the proportion of two parts of hydrogen to one of oxygen (or H_2O) and the current breaks up the water into its constituent parts. If brass or copper plates are used, the plate connected with the positive battery pole will be attacked by the action, and no oxygen will be evolved.

Experiment 32. — Reverse the direction of the current through the solution, by changing the battery terminals, and note that the hydrogen and oxygen gases are now liberated on the opposite electrodes from Experiment 31. This is another reason for supposing that the current has direction, the opposite deflections of the magnetic needle being a former proof

80. Electrolysis. — A large number of chemical compounds in a state of fusion, or dissolved in certain solvents, can, like the acidulated water, be separated into their constituent parts by the passage of an electric current through them Any substance that is capable of being decomposed by an electric current is called an *electrolyte* (as in a voltaic cell) and the process is termed *electrolysis* (meaning loosening by electricity). Plates of carbon, lead, platinum, or other metals are used to conduct the current to and from the solution. according to the substance to be electrolyzed.

These plates are called electrodes, and the plate by which the current *enters* the electrolyte is called the positive electrode or *anode* and the plate by which it *leaves* the solution is called the negative electrode or *cathode*. The constituent parts of the electrolyte which are liberated at the surface of the electrodes are called *ions*, the ion liberated at the positive electrode being called the *anion*, and that which appears at the negative electrode the *cation*. Any vessel or apparatus used for performing or measuring electrolysis is called a ***voltameter***. In the electrolysis of water hydrogen is the cation and oxygen the anion.

81. Electrolysis of Copper Sulphate. —

Experiment 33. — Fill the U-tube (Fig. 70) with a solution of copper sulphate, made by dissolving some copper sulphate crystals (bluestone) in water, and subject the solution to electrolysis, as in the case of the water, using platinum electrodes. Metallic copper is deposited upon

the negative electrode, that is, the plate becomes copper-plated. Oxygen gas is liberated at the positive platinum electrode and sulphuric acid is formed.

The chemical symbol for copper sulphate is $CuSO_4$. By electrolysis it is separated into Cu (metallic copper) and SO_4 (sulphion). The Cu goes to the negative plate while the SO_4 combines with water in the solution to form H_2SO_4 (sulphuric acid), and oxygen gas is liberated at the + platinum plate, as before. If the action is allowed to continue for some time, all the metallic copper is taken from the solution and deposited. This will be noted by the solution changing from a deep to a pale blue, as the change gradually takes place from copper sulphate to sulphuric acid. The action is represented as follows.

$$CuSO_4 = Cu + SO_4$$

Sulphate of copper becomes copper and sulphion.

$$SO_4 + H_2O = H_2SO_4 + O$$

Sulphion and water produce sulphuric acid and oxygen.

Experiment 34. – Reverse the direction of current in Experiment 33 and note that now the copper-coated platinum plate becomes the positive electrode, with a platinum plate for the negative electrode. The latter has metallic copper deposited upon it, while the former metallic copper on the positive plate is returned again to the solution.

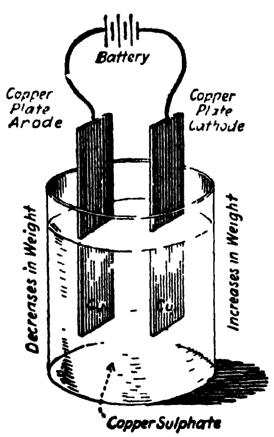


Fig. 71. — Copper Voltameter

Experiment 35. – Substitute two copper electrodes for the platinum electrodes and repeat Experiment 33. Metallic copper is again deposited upon the negative electrode (increasing its weight), but from the positive electrode no gas is evolved, yet this plate wastes away, or is dissolved in the solution, thereby losing in weight.

When a copper positive plate is used (Fig. 71), the $CuSO_4$ is separated into Cu, which is plated on the negative plate, and SO_4, which attacks the positive plate and forms a new molecule of $CuSO_4$ (copper sulphate). Thus as a molecule of copper sulphate is decomposed, a new

molecule is formed, keeping the solution of constant strength. Just as much metallic copper is thrown down into solution from the positive plate as is taken from the solution and deposited on the negative plate. The art of electroplating is based on the above experiments.

82. Electrolysis of Zinc Sulphate. —

Experiment 36. — Dissolve some crystals of zinc sulphate ($ZnSO_4$, white vitriol) in water. Refill the U-tube (Fig. 70) with this solution and subject it to electrolysis. Use platinum electrodes and metallic zinc is deposited upon the negative electrode and oxygen gas is evolved from the positive electrode. Reverse the direction of current. The previously deposited zinc goes again into solution, while the other electrode now receives a deposit of zinc. Oxygen gas is not evolved from the positive electrode till all of the zinc has been thrown down into solution.

Experiment 37. — Repeat Experiment 36, using two zinc strips as electrodes, and note that the positive strip wastes away and the negative zinc strip gains in weight. The action of the *Edison electrolytic meter*, formerly used for measuring current, is dependent upon this principle; it was a zinc voltameter.

83. Electrolysis of Lead Acetate. —

Experiment 38. — Prepare a solution of lead acetate, and pass it through filter paper to clear the solution. Fill the U-tube (Fig. 70) and subject it to electrolysis, using platinum electrodes. Metallic lead is deposited at the negative plate and oxygen gas appears at the positive plate. In addition to coating the platinum plate the lead will be deposited in a beautiful tree-like form extending out into the solution from the negative plate. The solution becomes weaker as the extraction of metallic lead continues. When the current is reversed the former positive plate receives the deposit in the "tree form," but oxygen gas is not now liberated from the positive plate, until the lead previously deposited is dissolved in the solution. This experiment is very suitable for illustration in a lantern projection cell, as well as for laboratory work.

84. Electroplating. — The art of depositing a coating of metal upon any object is termed *electroplating*, and is based upon the principles of electrolysis already explained. The metal held in solution is always deposited on the object to be plated, which must be connected to the negative pole of the source of electricity, while a plate of the metal from which the coating is derived, as nickel, copper, gold, or silver, is used as the positive plate. In plating with gold or silver the bath (electrolyte) is always alkaline, and generally a cyanide of

the metal to be deposited is used for the solution. In plating an iron spoon with silver, for example, the iron is cleaned, to remove all dirt and grease, and then first receives a deposit of copper in a copper bath, as silver will not deposit upon iron. Articles of iron, steel, zinc, tin, and lead cannot be silvered or gilded unless first coated with a thin covering of copper. After having been coated with copper, the spoon is transferred to a silver bath, properly connected up, and a coating of the desired thickness deposited, after which it is cleaned and brightened on a buffing wheel.

Other substances beside metals can be electroplated by first preparing the surface with a coating of powdered graphite, or plumbago, upon which metal can be deposited.

The character of the deposit depends upon the density or strength of current per square inch used (¶ 100). If electrolytic action takes place too rapidly, the deposit is soft, coarse-grained, and liable to prove unsatisfactory, while a small current gives a good, hard, close-grained deposit. A very low voltage is used in electroplating, the potential varying with the electrolytes used. The following voltages have been given as most suitable for the different metals.

Copper in sulphate	1.5–2.5 volts
Copper in cyanide	4.0–6.0 volts
Silver in cyanide	1.0–2.0 volts
Gold in cyanide	0.5–3.0 volts
Nickel in sulphate	2.5–5.5 volts

85. Electrotyping. — Suppose an electrotype is desired from a column of standing type. An impression in wax, or plaster of Paris, is carefully made of the type, and the wax mold dusted over with powdered graphite to make the surface a conductor. The mold is connected as the negative plate in a copper plating bath and receives a thin coating of metallic copper. After removal from the bath the copper deposit is removed from the mold and backed, or filled in, with type metal to about the depth of one-eighth inch. When cool, the back is planed smooth, fastened to a block of wood, and can then be used in the press. The copper mold is generally so thin that it is necessary to back it up with the type metal, owing to the pressure to which the electrotype is later sub-

jected. In this manner the electrotypes for the pages of many books are made from the standing type and may be used for taking thousands of impressions.

86. Polarity Indicator. — The positive and negative poles of a direct-current electric light, or power circuit, can be determined by dipping the terminals, at some little distance apart, into a tumbler of water. As twice as much hydrogen gas is evolved at the negative wire as oxygen at the positive wire the polarity of the circuit is readily determined. Care must be taken not to bring the wires into contact, or some damage would occur, due to too much current flowing through such a low-resistance circuit. A solution of iodide of potassium, with a little starch added, is sometimes sealed in a glass tube and terminals are provided by which a current can be passed through and the polarity of the circuit determined. This is called a polarity indicator. Iodine is liberated at the positive terminal and turns the starch blue around this terminal. Fig. 72 shows the form of a commercial polarity indicator now in general use, the liquid turns red at the negative terminal.



Fig. 72. — Polarity Indicator.

QUESTIONS

1. Name all the effects of an electric current and give a commercial application of each.
2. Explain the principle of an electric incandescent lamp.
3. How would you classify liquids according to their conducting power and the chemical effect of the current upon them?
4. What is an electrolyte? What is electrolysis?
5. Define the terms *anion*, *cathode*, *anode*, *cation*.
6. Describe the action in the copper voltameter, and give a sketch
7. Give two reasons for inferring that current has direction.
8. What is the action in a copper voltameter when a platinum plate is substituted for a copper plate? Give sketch.
9. What is a polarity indicator, and how is it used?
10. State how an electrotype is made.

LESSON VII

MEASUREMENT OF CURRENT

Strength of Current — Variation of Current and of the Current's Effects — How the Effects Vary with the Current Strength — Variation of Effects with the Same Current Strength through Dissimilar Apparatus — Measurement of Current Strength — Definition of the Unit of Current Strength — Definition of a Unit Quantity of Electricity — The Ampere-Hour — Weight Voltameters — Voltameter Calculations — Construction of the Gas Voltameter — Directions for Using the Gas Voltameter — Measuring Current Strength by a Gas Voltameter — Current Strength Used in Electroplating — Table VII — Questions and Problems.

87. Strength of Current. — The magnetic, the heating, or the chemical effect of an electric current may be employed to determine whether a current is flowing through a wire. If the magnetic effect of a current flowing through a wire is greater than that of another current, the *intensity* of the current, or the *strength* of the current, must be greater, since the magnitude of any of the current's effects varies with the current assumed to be flowing. We express the rate of flow of water through a pipe as so many *gallons per second*, which expression includes a definite quantity of water and a unit of time; that is, at a rate of flow of one gallon per second, we mean that one gallon passes any point in the pipe once every second. By the *strength of an electric current* we mean the rate of transfer of electricity past any point in the circuit in a unit of time (the second). It is obvious that the magnitude of the effects of the current may be used to measure the strength of the current.

88. Variation of Current and of the Current's Effects. —

Experiment 39. — Pass a current under a force of one volt through a coarse-wire galvanometer and note the deflection. Repeat the experiment with twice the applied pressure, two volts, and the deflection of the magnetic needle is *less than twice* as much as before, although the *force* is *doubled* and the *current strength*, varying as the force, must also *have been doubled.*

Experiment 40. — With an applied pressure of 4 volts note the amount of gas liberated from dilute sulphuric acid in 2 minutes by the apparatus shown in Fig. 73. Repeat the experiment with 8 volts, and note that in the same time twice the volume of gas is generated.

Experiment 41. -- Using copper sulphate and two copper plates, carefully weighed before the test, apply a force of 2 volts for 10 minutes and then reweigh the plates. The negative plate has gained in weight exactly what the positive plate has lost. Repeat the experiment with 4 volts for the same length of time and the change in weight is increased to double what it was before.

Experiment 42. Wind a number of turns of No. 30 iron wire around the bulb of a thermometer and place it in a small test tube containing a measured quantity of water. Place the test tube in a larger vessel containing sawdust to prevent heat radiation. Apply a force of 4 volts for 10 minutes and, by aid of the thermometer, note the rise in the temperature of the water. Repeat the experiment with 8 volts for the same period of time, with the same quantity of water, and at the previous starting temperature. Neglecting the heat lost by radiation, the increase of temperature is nearly four times as great as in the first test, although the current was only doubled. If the current had been tripled, the temperature rise would have been 9 times as great, and with the current quadrupled the rise would have been 16 times as great, and so on.

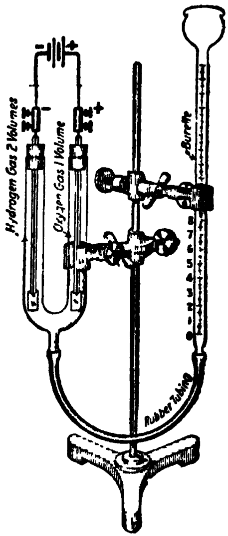


Fig. 73. — Student's Gas Voltameter.

Shows decomposition of water into H_2 and O.

89. How the Effects Vary with the Current Strength. The above experiments may be made simultaneously when the circuit is arranged as in Fig. 71, in which nearly all the effects of the current are represented. The circuit is made up as follows: starting from the positive battery terminal the current would flow (1) through a few turns of coarse wire in the galvanometer coil; (2) a large number of turns of coarse wire on the spools of the electromagnet; (3) a dilute solution of sulphuric acid in the mixed gas voltameter, the current to pass between platinum electrodes; (4) a solution of copper sulphate, the current to pass between copper electrodes; (5) a number of turns of fine iron wire wound around the bulb of a thermometer and immersed

in a vessel of water placed in sawdust; (6) through the carbon filament of an incandescent lamp; (7) through a switch to the negative pole of the battery, and (8) from the negative pole of the battery through it to the positive pole.

When the switch is closed, the current produces the following effects simultaneously: The magnetic needle is deflected; the keeper or armature is attracted by the electromagnet with a certain force in pounds; hydrogen and oxygen gas rise in the graduated test tube, displacing the acidulated water therein,

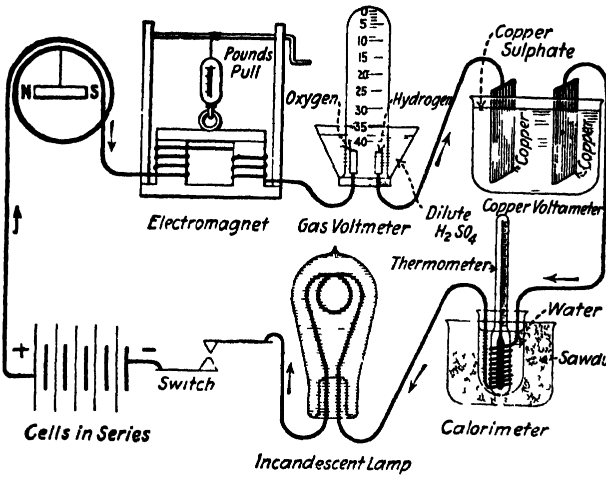


Fig 71 — The Effects of the Electric Current

This is a simple series circuit and the current is the same in all parts of it

metallic copper is dissolved from the copper positive plate and deposited upon the copper negative plate, so that it thereby gains in weight; heat is evolved in the vessel containing the coil of iron wire; light is given off by the incandescent lamp; zinc is being consumed in the battery furnishing the electrical energy to produce all the effects enumerated outside of the battery.

All the effects commence at the instant the switch is closed, but only four can be noted instantly — the needle's deflection, the attractive force of the magnet, the evolution of gas, and the

brilliancy of the lamp. The weight of copper deposited and of gas liberated, and the number of degrees rise in temperature, due to a current flowing for only an instant, are so small as to be practically unmeasurable. By allowing the current to flow for a certain period of time a measurable quantity is obtained, which, divided by the time in seconds, gives the magnitude of the effect per second. Keep the switch closed for about five minutes (5 × 60 = 300 seconds); then, by dividing the volume of gas generated in 300 seconds by 300, we obtain the gas generated per second, and similarly with the gain in temperature and the gain in weight of the negative copper plate.

We thus get a series of results of the different effects all corresponding to the same strength of an electric current, flowing for a unit of time. The intensity of current that deflected the needle in one part of the circuit, or magnetized the iron core of the electromagnet, is exactly the same as that which decomposed the acidulated water or the copper sulphate, or heated the iron wire. This is a simple *series* circuit, although made up of a number of different conductors, and the *current is the same in all parts of a series circuit;* that is, the rate of flow past any point selected is the same. The order of the arrangement of the apparatus is also immaterial. By increasing the E. M. F. of our battery so that twice the pressure is applied to this same circuit, we double the current strength or rate of flow. The switch is closed for the same time as before, and the results noted for comparison. A third test may also be made, using three times the force. The record of three such tests, with apparatus as arranged in Fig. 74, is approximately as follows:

Tests of Current Effects

	Test 1	Test 2	Test 3
Galvanometer, deflection in degrees	25	37	42
Electromagnet, pounds pull	5.4	9.5	13
Gas voltameter, cubic centimeters of gas generated per second	0.17	0.34	0.51
Copper voltameter, gain in grams per second	.0.0003	0.0006	0.0009
Calorimeter, degrees rise per second	0 1	0.4	0.9
Incandescent lamp, candle-power	1.5	5	25

From the above tests the following facts will be noted: The deflection of the galvanometer needle is not directly propor-

tional to the current, for doubling the current does not double the deflection. The attractive force of the magnet is not quite directly proportional to the current strength. The volume of gas generated is exactly proportional to the current, and if the current had been quadrupled the gas generated per second would have been four times as great, and so on. The deposit of copper is directly proportional to the current, doubling the current, also doubling the gain in weight. The rise in temperature of the calorimeter for twice the current strength was more than doubled, in fact it was increased fourfold; with three times the current strength the rise is ninefold — the temperature rise thus increases directly as the square of the current strength. The luminosity of the lamp increased very rapidly with the current.

90. Variation of Effects with the Same Current Strength through Dissimilar Apparatus. — If the series circuit, Fig. 74, had contained two pieces of each apparatus of widely varying dimensions of plates, convolutions in the coils, size of wire, etc., what would have been the result? The current strength would have been the *same* in *each* part of the circuit as before. The galvanometer of many turns would produce a larger deflection than one of few turns of the same diameter. The electromagnet, with the greater number of turns, would have the greater attracting power. A gas voltameter with small plates, widely separated, would evolve the *same volume* of gas as a voltameter with much larger plates placed close together, since the gas evolved is proportional only to the rate of flow of electricity, which is the same through both voltameters, and hence independent of the size and separation of the electrodes. Similarly, in two copper voltameters in the *same* series circuit, the weight of copper deposited is independent of the size of the plates or their distance apart, and would be the same for each voltameter, however constructed. More heat would be generated by the coil of many turns of fine wire than by the coil of few turns because of its higher resistance. The current flowing through a circuit is the same in all parts of that circuit; thus, if at two different points in a circuit a gas voltameter be inserted, the gas evolved at the one point will be exactly equal to that evolved at the other point.

91. Measurement of Current Strength. — To compare different strengths of current some arbitrary standard must be adopted. If we defined our unit of current as one of such strength as to deflect our magnetic needle (¶ 89) 25 degrees, it would be necessary to specify the length of needle, diameter of coil, number of turns, place where the needle was set up, etc.; these cumbersome specifications would make a unit so defined an impractical standard. Also, in the case of the electromagnet, all the dimensions of the core and keeper and of the wire, quality of the iron, etc., would have to be stipulated. If we would express the unit of current strength as such a rate of flow that would attract a keeper with a force of 5.4 pounds, then again 2 units of current would not attract the keeper with a force of 10.8 pounds, as might be expected, but only of 9.5 pounds, (see test, ¶ 89). The current strength is directly proportional, however, to the amount of gas generated per second or the amount of metal deposited per second, so that of all the effects the chemical one is the best adapted for furnishing a standard unit of current strength, since such a standard will be independent of the apparatus used to produce the effect. The heating and magnetic effects are employed in various practical instruments for measurements, but they are standardized by the chemical effect.

92. Definition of the Unit of Current Strength. — The strength of current is directly proportional to the amount of chemical decomposition it can produce in a given time. *That steady current which, when passed through a solution of nitrate of silver in water, in a silver voltameter, deposits silver at the rate of 0.001118 gram per second, is taken as a unit of current strength and called one ampere.*

One ampere will deposit in one second:

0.0003293 grams of copper in a copper voltameter;
0.0003387 grams of zinc in a zinc voltameter.

One ampere will also decompose 0.00009334 grams of dilute sulphuric acid per second. One ampere will also evolve 0.1733 cubic centimeters of mixed gas per second in a gas voltameter (when the temperature is 0° Centigrade and the atmospheric pressure is 76 centimeters of mercury).

93. Definition of a Unit Quantity of Electricity. — Distinction must be made between the total quantity of electricity that passes through a circuit in a given time and the rate of flow of electricity during that time. For example, at the rate of flow of one gallon per second, 3600 gallons of water would be delivered to a tank in an hour, the total quantity being readily distinguished from the rate of flow. We might take the *gallon per second* as a unit of rate of flow and name it, but this has not been done in hydraulics, although it is done in the case of electricity. The total quantity of water equals the rate multiplied by the time in seconds; thus, at a rate of flow of 8 gallons per second, in 60 seconds the total quantity delivered would be 480 gallons, which same quantity could be delivered to a tank in one second if the rate were 480 gallons per second, or in one half second if the rate were 960 gallons per second, or in 480 seconds if the rate were only one gallon per second. Similarly the *unit quantity of electricity is the amount of electricity that flows per second past any point in a circuit when the current strength is one ampere, and this unit quantity has been called the coulomb.* If a current of one ampere flows for 60 seconds, then the total quantity is 60 ampere-seconds, or 60 coulombs of electricity.

FIRST: TO FIND THE TOTAL QUANTITY OF ELECTRICITY IN COULOMBS PASSING THROUGH A CIRCUIT IN A GIVEN TIME:

Multiply the current strength (expressed in amperes) by the time (expressed in seconds).

Let I = current in amperes,
Q = total quantity of electricity in coulombs,
t = time the current flows in seconds.

Then, since

quantity = current strength × time,

or coulombs = amperes × seconds,

it follows that

$$Q = I \times t \qquad (16).$$

Problem 14. — An incandescent lamp requires a current of one half an ampere to maintain its proper brilliancy. If the lamp is illuminated for two hours what quantity of electricity will traverse the lamp?

$t = 2$ hours $= 60 \times 60 \times 2 = 7200$ seconds.

By Formula (16) $Q = I \times t = \frac{1}{2} \times 7200 = 3600$ coulombs

SECOND: TO FIND THE AVERAGE CURRENT STRENGTH (IN AMPERES) WHEN THE TIME OF CURRENT FLOW AND THE QUANTITY OF ELECTRICITY ARE KNOWN:

Divide the quantity (in coulombs) by the time (in seconds).

Current strength = quantity ÷ time,

or amperes = coulombs ÷ seconds,

whence, $$I = \frac{Q}{t} \quad \text{. . . . .} \quad (17).$$

Problem 15. — What is the average current in a lamp circuit if the quantity of electricity traversing that circuit in 5 hours is 54000 coulombs?

5 hours = 60 × 60 × 5 = 18000 seconds.

By Formula (17) $I = \frac{Q}{t} = \frac{54000}{18000} = 3$ amperes.

THIRD: TO FIND THE TIME (IN SECONDS) REQUIRED FOR A GIVEN QUANTITY OF ELECTRICITY (IN COULOMBS) TO PASS A POINT IN A CIRCUIT:

Divide the quantity of electricity (in coulombs) by the rate of flow (in amperes).

$$\text{Time} = \frac{\text{quantity}}{\text{current strength}},$$

or $$\text{seconds} = \frac{\text{coulombs}}{\text{amperes}},$$

or, by substitution, $$t = \frac{Q}{I} \quad \text{. . . . .} \quad (18).$$

Problem 16. — How long a time will be required to pass 18000 coulombs through an electroplating bath if the average current strength is 6 amperes?

By Formula (18) $t = \frac{Q}{I} = \frac{18000}{6} = 3000$ seconds, or $\frac{3000}{60} = 50$ minutes

94. The Ampere-Hour. — The *coulomb* is a very *small unit* of quantity. A *larger unit*, the *ampere-hour*, is often used. One *ampere-hour* would be the quantity of electricity that would pass any point in a circuit in one hour, when the strength of current is one ampere. One ampere-hour obviously equals 2

amperes for one-half hour; 4 amperes for one-quarter hour, or one-quarter ampere for 4 hours, and so on. One ampere-hour also equals 3600 coulombs.

The capacity of batteries is rated in ampere-hours. For example, a 100-ampere-hour cell would mean one in which sufficient chemicals were present to maintain 10 amperes for 10 hours; 5 amperes for 20 hours, etc. An ampere-hour recording meter may be placed in a circuit to record the total quantity of electricity that has been utilized, or the total ampere-hours.

Problem 17. — A current of 6.5 amperes was maintained by a cell for 4 hours. What quantity of electricity has been used?

$$\text{Quantity} = \text{amperes} \times \text{hours} = 6.5 \times 4 = 26 \text{ ampere-hours.}$$

Suppose the cell has a capacity of 80 ampere-hours, how long could the above current be maintained?

$$\text{Hours} = \frac{\text{ampere-hours}}{\text{amperes}} = \frac{80}{6.5} = 12.3 \text{ hours.}$$

95. Weight Voltameters. — Current strength may be determined by a weight voltameter, one in which the weight of metal deposited or weight of water decomposed serves to determine the rate of flow, or by a gas voltameter, in which the volume of mixed gas to be evolved is used to determine the current strength A weight voltameter is illustrated in Fig. 75; the plates are supported by arm A which can be rotated about the swivel B. The two outside plates form the anode, and are joined to one binding post, while the cathode is placed between them and connected to the other binding post. The cathode thus receives a deposit on both sides. An adjustable arm controlled by pinion P serves to lower the plates into the electrolyte.

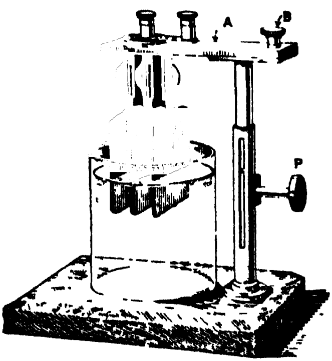


Fig. 75. — Construction of a Weight Voltameter.

One cathode between two anodes

96. Voltameter Calculations. — FIRST: TO CALCULATE THE STRENGTH OF AN UNKNOWN CURRENT (IN AMPERES) WHICH HAS PASSED THROUGH A WEIGHT VOLTAMETER:

Find the weight of metal deposited per second by dividing the total gain in weight by the time (in seconds) the current flows through the instrument; divide this quotient by the weight deposited by one ampere in one second.

Let I = current in amperes,
W = total gain in weight,
t = time of current flow in seconds,
K = mass deposited by one ampere in one second, that is by one coulomb.

Substituting for the above statement.

$$\text{Amperes} = \frac{\text{weight gained}}{\text{gain per coulomb} \times \text{time}},$$

or

$$I = \frac{W}{K \times t} \quad \ldots\ldots\ldots\ldots\ldots \quad (19).$$

If W is expressed in grams:

K for a copper voltameter is 0.0003293 gram,
K for a zinc voltameter is 0.0003387 gram,
K for a silver voltameter is 0.001118 gram,
K for nickel voltameter is 0.000304 gram,
K for a sulphuric acid *weight* voltameter is 0.00009334 gram,
K for a sulphuric acid *gas* voltameter is 0.1733 cubic centimeter.

Problem 18. — The negative plate of a copper voltameter has increased in weight by 1.818 grams in thirty minutes. What was the average current strength?

K for copper is 0 0003293, t = 30 minutes = 30 × 60 = 1800 sec.

By Formula (19) $I = \frac{W}{K \times t} = \frac{1.818}{0.0003293 \times 1800} = 3.067$ amperes.

SECOND: TO FIND THE WEIGHT OF ANY METAL THAT WILL BE DEPOSITED IN A VOLTAMETER BY A GIVEN CURRENT IN A GIVEN TIME:

Multiply the current strength by the time (in seconds) and this product by the weight deposited by one ampere in one second (K);

the result is the weight expressed in grams (one pound = 453.59 grams).

$$\text{Weight (gained)} = \text{current} \times \text{time} \times K,$$

or

$$W = I \times t \times K \quad . \; . \; . \; . \; . \; . \quad (20).$$

Problem 19. — In an electroplating bath how many grams of zinc will be deposited by a current of 5 amperes in 45 minutes?

K for zinc = 0.0003387, t = 45 minutes = 45 × 60 = 2700 seconds.

By Formula (20) $W = I \times t \times K = 5 \times 2700 \times 0.0003387 = 4.572$ grams.

THIRD: TO FIND THE TIME REQUIRED TO ELECTROLYTICALLY DEPOSIT ANY GIVEN WEIGHT OF METAL WITH A GIVEN CURRENT:

Divide the weight by the current strength, and by the weight deposited by one ampere in one second (K); the result is the time expressed in seconds.

$$\text{Time} = \frac{\text{weight (gained)}}{\text{current} \times K},$$

or

$$t \text{ (seconds)} = \frac{W}{I \times K} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (21).$$

Problem 20. — How long a time will be required to deposit 5.93 grams of silver on a copper-plated teaspoon with a current of 2 amperes?

K for silver = 0.001118 gram.

By Formula (21) $t = \frac{W}{I \times K} = \frac{5.93}{2 \times 0.001118} = 2652$ seconds, or $\frac{2652}{60}$
= 44 minutes 12 seconds.

97. Construction of the Gas Voltameter. — The gas voltameter is convenient for individual laboratory use with a large body of students, as it obviates the necessity of a pair of scales for each student. A demonstration type of instrument is shown in Fig. 76. The battery terminals, T, lead to the platinum electrodes, Pt. Dilute sulphuric acid is poured in at F and is decomposed by the current into H and O, these gases may be removed for test by opening the stopcocks, SC.

A student's voltameter is illustrated in Fig. 73 and is composed as follows:

1 metal stand (16 inches high)
1 glass U-tube
2 platinum electrodes sealed in a glass tube and connected by a copper wire, to which connectors are attached
2 rubber stoppers or corks for electrodes
1 glass burette, graduated from 0 to 20 cubic centimeters and reading in tenths of a cubic centimeter
2 adjustable clamps
8 inches of rubber tubing
2 brass connectors.

98. Directions for Using the Gas Voltameter. — (1) Attach both clamps to the stand. (2) Attach one end of the rubber tube to the glass U-tube and *carefully* clamp it by the lower clamp on to the stand. (3) Attach the other end of the rubber tube to the burette and *carefully* clamp it by the upper clamp. (4) Adjust the position of both clamps so that the zero mark on the burette is about one half inch below the level of the top of the U-tube. (5) Pour the acidulated water into the mouth of the burette till the water in the U-tube is about one half inch from the top; the height of liquid in the burette should be on a level with or *above* the zero mark. (6) With the electrodes inserted through the corks, place each one in position *carefully*, by giving a slight twist to the right as the cork enters. (7) The water level in the U-tube and burette should now be the same, or further adjustment must be made to attain this result. The water level in the burette does not necessarily have to correspond with the zero graduation, but must not be below it. (8) Unclamp the burette and hold it nearly horizontal. The liquid will not run out if the corks are tight, so that this is an *air leakage test*. (9) Attach the connectors to the wires from the source of E. M. F. (which should be 2 or more volts); a switch is preferably included in the circuit.

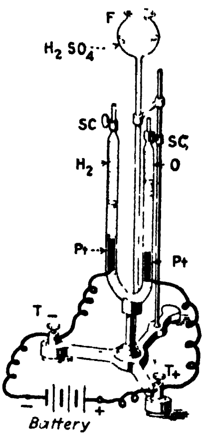


Fig. 76. — Gas Voltameter.
Hoffman's lecture-room form

In electrolyzing any substance a back or contrary E. M. F. is set up in opposition to the decomposing current, due to the chemical affinity of the substances disunited, which tend to reunite. Sufficient force must therefore be applied to overcome this force of chemical affinity. For example, in the case of water this opposing force is about 1.5 volts, so that it requires a greater force than 1.5 volts to electrolyze water, hence two cells are joined in series.

Experiment 43. — Close the switch connecting the above voltameter in circuit. Bubbles of gas rise in the U-tube from both electrodes, displace the water, and force it up the burette. Twice the volume of gas (hydrogen) is collected over the negative electrode than is collected over the positive electrode (oxygen). Run the test till the volume of hydrogen gas occupies nearly the whole limb of the U-tube, when the switch should be opened.

Experiment 44. — With the gases collected in Experiment 43, lower the burette as far as possible (to decrease the hydrostatic head). Remove the cork for an instant from the hydrogen limb and *quickly* apply a lighted match. The hydrogen burns with a pale bluish flame. *Replace the cork quickly* so that the solution is not forced out of the U-tube. Now remove the cork from the oxygen limb, extinguish the flame of the match, and *quickly* apply the glowing spark to the oxygen; the match immediately bursts into a flame again. *Replace the cork quickly.* Oxygen gas does not burn, but supports combustion. If both gases are collected in a single tube, as in the form of voltameter shown in Fig. 74, and a lighted match is presented to the mouth of this tube the hydrogen, instead of burning, explodes with a violent report, due to the presence of the oxygen.

99. Measuring Current Strength by a Gas Voltameter. — TO FIND THE CURRENT STRENGTH WHEN A DEFINITE VOLUME OF GAS IS EVOLVED IN A GIVEN TIME:

Divide the volume of gas evolved by the time (in seconds) and this quotient by the volume of gas evolved by one ampere in one second (K). The result is the current in amperes (subject to corrections when greater accuracy is required).[1]

$$\text{Current in amperes} = \frac{\text{cu. cm. of gas generated}}{\text{time (seconds)} \times K},$$

or

$$I = \frac{V}{t \times K} \quad \ldots\ldots\ldots\ldots \quad (22).$$

K for the mixed gases from water or the two gases evolved separately = 0.1733 cubic centimeters (¶ 92).

The volume of gas (in cubic centimeters) which will be evolved by a given current in a given time is

$$\text{volume evolved (cu. cm.)} = \text{current} \times \text{time (seconds)} \times K,$$

or

$$V = I \times t \times K \quad \ldots\ldots\ldots \quad (23).$$

Also the time required to evolve a certain quantity of gas with a given current is

$$t = \frac{V}{I \times K} \quad \ldots\ldots\ldots \quad (24).$$

[1] Neglecting temperature, barometric pressure and hydrostatic head.

Experiment 45. — Set up the gas voltameter again according to the directions in ¶ 98. To correct the error caused by the decrease in volume of the gases, due to the weight of the liquid in the burette at the end of the test, lower the burette before the test so that the height of liquid in it is about on a level with the bottom of the U-tube. Secure a watch (preferably with a second hand). Note the level of the liquid on the burette scale before starting the test. Close the switch, noting the exact time. Allow the gas to be evolved till either the hydrogen limb of U-tube is nearly full, or the liquid in the burette *approaches* the end of the scale. *Do not run above scale limit.* Note the time of opening the switch, also the *height* of the liquid in the burette.

Problem 21. — The following data are recorded in Experiment 45. Find the strength of current.

Level in burette before test 2.6 cu. cm
Level in burette after test 28.8 cu. cm
Volume of gas evolved = 28.8 – 2.6 = 26.2 cu. cm.
Time of closing switch 8.40.
Time of opening switch 8.45.
Length of run = 5 minutes = 5 × 60 = 300 seconds.

Volume of gas generated per second $= \frac{26.2}{300} = 0.0873$ cu. cm.

One ampere in one second (one coulomb) generates 0.1733 cubic centimeters of gas per second, therefore the current is $\frac{0.0873}{0.1733} = 0.5$ ampere,

or by Formula (22) $I = \frac{V}{K \times t} = \frac{26.2}{0.1733 \times 300} = 0.5$ ampere.

When more accurate calculations are desired the following formula is used to find the current strength:

$$I = \frac{V \times h \times 273}{0.1733 \times 76\,(273 + C^{\circ}) \times t} \quad . \; . \; . \; . \quad (25).$$

where V = volume of gas in cubic centimeters,
h = height of barometer in centimeters of mercury,
C° = temperature of room where test is made in degrees Centigrade.
t = time (in seconds) during which gas is evolved.

Problem 22. — In an experiment the volume of gas generated in a gas voltameter was found to be 20 cubic centimeters in 50 seconds, its temperature (taken as the temperature of the room) being 20 degrees Centigrade. The pressure of the atmosphere was equal to 75 centimeters of mercury. What was the current strength?

By Formula (25)

$$I = \frac{20 \times 75 \times 273}{0.1733 \times 76\,(273 + 20) \times 50} = 2.12 \text{ amperes.}$$

To find the volume of gas generated by a known current use the formula:

$$V = \frac{0.1733 \times I \times 76\,(273 + C^\circ) \times t}{h \times 273} \quad . \quad . \quad . \quad (26).$$

Problem 23. — What volume of gas would be produced in a gas voltameter in 30 seconds by a steady current of 18 amperes, supposing the temperature of the gas so produced is 20 degrees C. and the barometer stands at 77.5 centimeters?

By Formula (26) $V = \frac{0.1733 \times 18 \times 76(273 + 20) \times 30}{77.5 \times 273} = 98.49$ cu. cm.

100. Current Strength Used in Electroplating. — If the metallic deposition is performed too rapidly the deposit becomes open and of a powdery appearance. A low current density produces a hard, close-grained surface. The usual densities used in practice as reckoned on the area to be plated are:

Copper acid bath, 10 to 12 amperes per square foot.
Copper cyanide bath, 6 to 8 amperes per square foot.
Nickel, double sulphate, 4 to 6 amperes per square foot.
Gold, chloride in cyanide, 1 to 2 amperes per square foot.
Silver, double cyanide, 2 to 5 amperes per square foot.

Problem 24. — A piece of sheet-iron, six inches square, is to be plated on both sides in a copper acid bath. What current strength is required?

Area of plate (both sides) $= 6 \times 6 \times 2 = 72$ square inches

$$= \frac{72}{144} = 0.5 \text{ square foot.}$$

At 11 amperes per square foot, the required current is 5.5 amperes.

Table VII. Approximate Values of Current Used in Commercial Apparatus

For a 110-volt, 16-candle-power, carbon incandescent lamp	0.5 ampere
For a 110-volt, 20-candle-power, "Mazda" tungsten incandescent lamp	0.23 ampere
For an enclosed 110-volt arc lamp	5 amperes
For an open-air arc lamp	8 to 10 amperes
For a 220-volt 25-horse-power motor when fully loaded	94 amperes
For a 110-volt fan motor	½ to 2 amperes
For the average electric bell	$\frac{1}{10}$ ampere
For the average telegraphic circuit	0.025 ampere
For a 110-volt voltmeter, full-scale deflection	0.006 ampere
For electric welding	20 to 50,000 amperes

QUESTIONS

1. What do you understand by *current strength?*

2. State some experiments you would make to ascertain how the effect of a current varies with its strength.

3. Which effects of the current are directly proportional to it?

4. Which effects do not vary directly with the current strength?

5. An electromagnet attracts its keeper with a force of 18 pounds. If twice the E. M. F. be applied to the magnet coils, what will be the comparative result?

6. A coil of iron wire carrying a current is placed into a tumbler of water for 10 minutes and the temperature is changed 6 degrees. The current is then exactly doubled and maintained for the same length of time What is the change in temperature?

7. Which is the most suitable effect of the current by which it can be measured? Give reason for your answer.

8. What would be the objection to considering as the standard unit of current strength one of such a strength that would deflect a galvanometer needle 30 degrees?

9. What is the unit of current strength? A current is said to be 5 amperes. What do you understand by this expression?

10. Explain the difference between the terms "current strength" and "quantity of electricity."

11. What is the unit of electrical quantity? Five coulombs pass every second through a lamp. What is the current strength?

12. Why is it that you cannot electrolyze water with one Daniell cell?

13. Platinum and copper plates are dipped into a solution of zinc sulphate and a current is passed from the platinum to the copper plate. How are the plates affected?

14. Copper and platinum plates are dipped into copper sulphate. What is the action when the current is passed from the copper to the platinum plate?

PROBLEMS

1. How many ampere-hours will be recorded by a meter through which 160 amperes are flowing for three quarters of an hour? *Ans.* 120 ampere-hours.

2. A 100-ampere-hour Edison-Lalande cell is discharged through an electromagnet at a $2\frac{1}{2}$ ampere rate. How long will the cell maintain this current through the magnet? *Ans.* 40 hours.

3. A meter records 500 ampere-hours. It was in circuit 5 days for 10 hours each day. What was the average current used? *Ans.* 10 amperes.

4. How many coulombs have passed through an arc lamp in three quarters of an hour if the current was 10 amperes? *Ans.* 27,000 coulombs.

5. What current strength is required to deposit 5 grams of copper upon an iron spoon in 35 minutes? *Ans.* 7.219 amperes.

6. A meter records 54,000 coulombs in 3 hours. What was the average current? *Ans.* 5 amperes.

7. How many grams of copper will be deposited on an iron plate used for a ship's hull in 10 hours if the average current is 25 amperes? *Ans.* 296.37 grams or 0.654 pound.

8. The two terminals of an electric-light circuit are dipped into a tumbler containing 5 grams of acidulated water. How long would a current of 3 amperes flow before the water was entirely decomposed? *Ans.* 4 hours 57 min. 35 sec.

9. Using a current density of 5 amperes per square foot, how long a time is required to copper-plate both sides of a square iron plate measuring 4 feet on a side, supposing sufficient thickness is attained when the coating weighs 1 grams per square foot? *Ans.* 10 min. 29 sec.

10. An inverted test tube, capacity 10 cu. cm., is filled with acidulated water, and the terminals of a battery having several cells in series are introduced underneath the tube. In 5 minutes half of the tube was filled by gas. What was the strength of current in the circuit? *Ans.* 0.384 ampere.

11. The negative zinc plate of an Edison electrolytic meter increased in weight, during a certain time, by 3.455 grams. This amount represents one one-thousandth part of the current used by the consumer. With how many ampere-hours should he be charged? *Ans.* 2833 ampere hours.

12. What bill would you render for the electricity used in Problem 11 if the rate was 1.5 cents per ampere-hour? *Ans.* $42.50.

LESSON VIII

OHM'S LAW

Electromotive Force (Pressure) — Electromotive Forces in Practice — Table VIII — Ohm's Law — Circuits and their Resistance — Resistances in Series — Equal Resistances in Parallel (Joint Resistance) — Conductance of a Circuit — Unequal Resistances in Parallel — Conductance Method for Conductors in Parallel — Resistances Joined in Multiple-series — Division of Current in a Divided Circuit — Ohm's Law Applied to a Battery Circuit — Questions and Problems.

101. Electromotive Force (Pressure). — Electromotive force, which is the primary cause of a flow of electricity, has been defined (¶ 35) as the force which moves or tends to move electricity. The various terms *electromotive force, pressure, difference of potential,* and *voltage* are frequently used to signify the same thing, namely, that force which moves, or tends to move, electricity against the resistance of a conductor.

The electromotive force set up by a voltaic cell is the result of the *difference of potential* set up between the two plates and proportional to it. Just as in water pipes, where a difference in level produces a *pressure* which causes a flow of water the instant a valve is opened, so in an electric circuit a difference of potential produces an E. M. F. which sets up a current the instant the circuit is completed for the electricity to flow through. In the case of both water pipes and electric circuits there may be a great pressure and yet no flow of water or electricity. If the flow of water is prevented by a closed valve, there will be no flow or current so long as the valve is closed, yet there may be a high pressure. If the path of the electricity is stopped by a switch being open or by a broken wire, there will be no flow of current (amperes), so long as the switch is open, though the pressure (volts) may exist at the terminals of the battery or generator; in Fig. 37 there can be no flow of electricity in the wire held over the magnetic needle until the

circuit is completed by closing the switch, yet there is a pressure between the switch points.

There is one other *factor*, in addition to the pressure, that determines the amount of the current, both of water and of electricity. This *factor* is the *resistance* of the wires and electrical device in the case of electricity, and the *resistance* of the pipes and hydraulic device in the case of water. The greater this resistance the less the current under the same pressure. Resistance has been fully explained in Lesson V.

If the voltage impressed on a circuit is increased, the current flow will be correspondingly increased, as would the flow of water through a pipe, if the water pressure causing the flow was increased.

Experiment 46. – Connect a Daniell cell in series with spool No. 4 of the resistance set (¶ 67) and a detector galvanometer, and note the value of the deflection. Now substitute a bichromate cell for the Daniell cell, using the same spool, and the deflection is greater than before. The E. M. F. of the bichromate cell is higher than that of the Daniell cell, and therefore causes a larger current to flow through the same resistance. Any other type of cell used would cause more or less current to flow through the spool, depending upon its E. M. F. (pressure in volts).

In a battery, the E. M. F. is dependent on the nature of the plates and the solution used, *but independent of their size or distance apart.*

In a generator the E. M. F. is set up by revolving a bundle of wires in a magnetic field, and depends upon the strength of the field, the number of wires revolved, and the speed.

102. Electromotive Forces in Practice. — The following table gives values of some E. M. F's met with in direct-current practice:

Table VIII. Voltage Values

Voltaic cells	0.7 to 2.0	volts	Lighting circuits	110 to 120	volts
Edison storage cell	1.2	"	Motor circuits	120 and 240	"
Lead storage cell	2.1	"	Electric railways	500 to 3000	"
Electroplating	4 to 12	"	Plate voltage of large radio transmitters	5000 to 15.000	"
Telephone circuits	24 and 48	"			

Generators may develop from a few volts to thousands of volts, according to the purpose for which they are designed.

103. Ohm's Law. — IN ANY CIRCUIT THROUGH WHICH A CURRENT IS FLOWING THE THREE FOLLOWING FACTORS ARE PRESENT: (1) THE *pressure* OR POTENTIAL DIFFERENCE, EXPRESSED IN *volts*, CAUSING THE CURRENT TO FLOW. (2) THE OPPOSITION OR *resistance* OF THE CIRCUIT, EXPRESSED IN *ohms*, WHICH MUST BE OVERCOME. (3) THE *current strength*, EXPRESSED IN *amperes*, WHICH IS MAINTAINED IN THE CIRCUIT, AS A RESULT OF THE PRESSURE OVERCOMING THE RESISTANCE. A DEFINITE AND EXACT RELATION EXISTS BETWEEN THESE THREE FACTORS, PRESSURE, CURRENT STRENGTH, AND RESISTANCE IN ANY CIRCUIT, WHEREBY THE VALUE OF ANY ONE FACTOR MAY ALWAYS BE CALCULATED WHEN THE VALUES OF THE OTHER TWO FACTORS ARE KNOWN. THIS RELATION, KNOWN AS *Ohm's Law, is very important*, SINCE IT FORMS THE BASIS FOR ALL CALCULATIONS IN ELECTRICAL ENGINEERING. IT MAY BE SUMMARIZED AS FOLLOWS:

First. — The current in any electric circuit is equal to the electromotive force applied to the circuit, divided by the resistance of the circuit.[1]

Let E = E. M. F. or available pressure, expressed in volts, applied to any circuit,
R = resistance of the circuit, expressed in ohms,
I = current strength, expressed in amperes, to be maintained through the circuit.

Then, by the above statement of Ohm's Law,

$$\text{current} = \frac{\text{pressure}}{\text{resistance}},$$

or

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}},$$

or

$$I = \frac{E}{R} \quad \dots\dots\dots\dots \quad (27).$$

The following five statements and formulæ are directly derived from the above general statement of Ohm's Law, and are all therefore included in the expression I = E ÷ R.

[1] Ohm's Law, as stated above, applies to direct currents flowing in any circuit. It is modified to some extent in alternating-current calculations. See ¶ 350.

Problems are solved under each case to illustrate the interpretation of each statement made.

Problem 25. — An incandescent lamp has a resistance (hot) of 220 ohms, and is connected to electric-light mains, across which 110 volts potential difference is maintained. What current will flow through the lamp?

By Formula (27) $I = \frac{E}{R} = \frac{110}{220} = \frac{1}{2}$ ampere.

Second. — The current strength in any circuit increases or decreases directly as the E. M. F., or potential difference, increases or decreases, when the resistance is constant. With a constant pressure the current increases as the resistance is decreased, and decreases as the resistance is increased. Briefly, the current varies directly as the E. M. F. and inversely as the resistance.

Since $I = \frac{E}{R}$, it follows that with R constant, I varies directly as E. With E constant the greater R, the less I, and *vice versa*.

Problem 26. — In Problem 25, if the pressure is increased from 110 to 220 volts, what current will the lamp receive, assuming the resistance constant?

By Formula (27) $I = \frac{E}{R} = \frac{220}{220} = 1$ ampere.

This problem illustrates the increase of I with increase of E with a constant R.

Problem 27. — In Problem 25, if the pressure is reduced to 55 volts, what current will the lamp receive?

By Formula (27) $I = \frac{E}{R} = \frac{55}{220} = \frac{1}{4}$ ampere.

This problem illustrates the decrease of I with the decrease of E when R is constant.

Problem 28. — In Problem 25, if a lamp of 110 ohms resistance is used, what current will it receive?

By Formula (27) $I = \frac{E}{R} = \frac{110}{110} = 1$ ampere.

With E constant, I increases as R decreases.

Problem 29. — In Problem 25, if a lamp of 440 ohms is used, what current will it receive?

By Formula (27) $I = \frac{E}{R} = \frac{110}{440} = \frac{1}{4}$ ampere.

Therefore, as R increases, when E is constant, I decreases.

Third. — *The electromotive force required to maintain a certain current strength in a circuit of known resistance, is numerically equal to the product of the current and the resistance.*

By the above statement,

$$\text{pressure} = \text{current} \times \text{resistance},$$

or

$$\text{volts} = \text{amperes} \times \text{ohms},$$

or

$$E = I \times R \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(28)}.$$

Problem 30. — What pressure is required to cause 10 amperes to flow through an electrical appliance if the resistance is 4.5 ohms?

By Formula (28) $E = I \times R = 10 \times 4.5 = 45$ volts.

Fourth. — *The pressure varies directly as the current and resistance. For example, if a greater current is to be sent through the same resistance, a greater pressure must be applied; also, if the same current is to be passed through a higher resistance a greater pressure must be applied.* $E = I \times R$.

Problem 31. — What pressure is required to cause 15 amperes to flow through the device in Problem 30?

By Formula (28) $E = I \times R = 15 \times 4.5 = 67.5$ volts.

Problem 32. — If the device in Problem 30 had a resistance of 9 ohms, what pressure must have been applied to have had 10 amperes flow through it?

By Formula (28) $E = I \times R = 10 \times 9 = 90$ volts.

Problems 31 and 32 illustrate how E increases directly with R and I. If either R or I had been decreased E would have been decreased also.

Fifth. — *The resistance required to be inserted in any circuit, so that a given current will flow by reason of a known pressure, is equal to the pressure to be applied, divided by the current that is to be maintained.*

By the above statement,

$$\text{resistance} = \frac{\text{pressure}}{\text{current}},$$

or

$$\text{ohms} = \frac{\text{volts}}{\text{amperes}},$$

$$R = \frac{E}{I} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(29)}.$$

Problem 33. — An electric heater is constructed of No. 18 iron wire and is placed across 110 volts. If it takes a current of 10 amperes, what will be the value of its hot resistance?

By Formula (29) $R = \frac{E}{I} = \frac{110}{10} = 11$ ohms (hot).

Sixth. — *The resistance required for any circuit varies directly with the pressure applied, and inversely as the value of the current to be maintained.* For example, with a *constant pressure* the resistance must be halved if the current is to be doubled; on the other hand, with a *constant current* to be maintained in a circuit at double the pressure, the resistance must be doubled.

Problem 34. — What should be the resistance of an electric heater which will take a current of 20 amperes on a 110-volt circuit?

By Formula (29) $R = \frac{E}{I} = \frac{110}{20} = 5.5$ ohms.

Compare with Problem 33.

Problem 35. If the pressure is 220 volts in Problem 33, what resistance will be required?

By Formula (29) $R = \frac{E}{I} = \frac{220}{10} = 22$ ohms

104. Circuits and their Resistance. — There are two simple ways of connecting two or more pieces of electrical apparatus. First, when the pieces are connected, as are the coils A and B in Fig. 77, they are said to be in *series*, and the same current (amperes) will flow through each piece of apparatus so connected regardless of its resistance. Second, when the pieces of apparatus are connected so that the total current is divided between them, they are said to be in *parallel* with each other, as the coils A and B in Fig. 78. *Multiple* or *shunt* are other names for the connection of apparatus in this manner. The ten lamps in Fig. 79 are in parallel with each other.

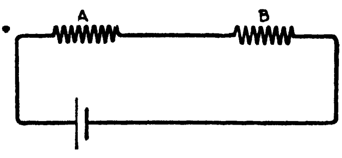


Fig. 77. — Two Resistances in Series

The two combinations, series and parallel, may exist in the same circuit as in Fig. 80, where the parallel combination of lamps C and D is in series with the series combination of

lamps A and B. Also, there may be a multiple of series combinations, as in Fig. 83, where lamps A and B are in series, and then in parallel with the series combination of lamps C and D; this is termed a *multiple-series* connection. The cells of a battery are sometimes connected in this manner (¶ 123)

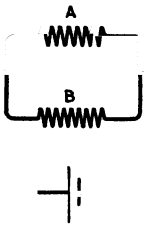


Fig. 78. — Two Resistances in Parallel.

105. Resistances in Series. — TO FIND THE TOTAL RESISTANCE OF A NUMBER OF RESISTANCES CONNECTED IN SERIES:

Find the sum of the resistances connected. If in Fig. 77, A equals 40 ohms and B equals 160 ohms, then the total resistance equals 40 + 160 = 200 ohms. The same current will flow through A as through B.

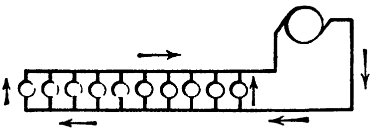


Fig. 79 — Ten Incandescent Lamps Connected in Parallel to a Generator.

106. Equal Resistances in Parallel. — **Joint Resistance.** In Fig. 78 the two resistances, A and B, are connected in parallel, and then to the battery. If the resistance of A is equal to that of B, the conductance will also be equal and the current will divide, one half flowing through A and the other half through B. Since the total area of the conducting circuit has been increased, the combined or *joint resistance* of A and B will be less than either resistance separately. If the resistance of A equals that of B, then the area will have been doubled, and the joint resistance equal to one half that of A or B. Thus, if A and B = 10 ohms each; joint resistance = ½ of 10 or 5 ohms. With three equal resistances in parallel the joint resistance will be ⅓ the value of one of the resistances.

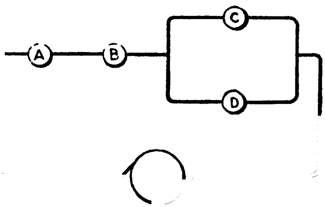


Fig. 80. — Two Incandescent Lamps in Parallel and in Series with Two Lamps in Series.

TO FIND THE JOINT RESISTANCE OF ANY NUMBER OF EQUAL RESISTANCES CONNECTED IN PARALLEL:

Divide the value of a single resistance by the number connected in parallel.

Let R = a single resistance,
nq = number of equal resistances in parallel,
J. R. = joint resistance.

Then, $$J.R. = \frac{R}{nq} \quad \ldots\ldots\ldots\ldots \quad (30).$$

TO FIND THE NUMBER OF EQUAL RESISTANCES CONNECTED IN PARALLEL (nq) WHEN THE JOINT RESISTANCE (J. R.) AND THE VALUE OF A SINGLE RESISTANCE (R) ARE KNOWN:

Divide the value of a single resistance by the joint resistance.

Thus, $$nq = \frac{R}{J.R.} \quad \ldots\ldots\ldots\ldots \quad (31).$$

TO FIND THE VALUE OF A SINGLE RESISTANCE (R) WHEN THE JOINT RESISTANCE AND THE NUMBER OF EQUAL RESISTANCES IN PARALLEL ARE KNOWN:

Multiply the joint resistance by the number of equal resistances connected in parallel.

$$R = J.R. \times nq \quad \ldots\ldots\ldots\ldots \quad (32).$$

Problem 36. — Ten incandescent lamps are connected in parallel (Fig. 79). Each lamp has a resistance (hot) of 220 ohms. What is the total or joint resistance of the lamp circuit?

By Formula (30) $J.R. = \frac{R}{nq} = \frac{220}{10} = 22$ ohms.

Problem 37. - The joint resistance of 55 lamps connected in parallel is 4 ohms. What is the resistance of 1 lamp?

By Formula (32) $R = J.R. \times nq = 4 \times 55 = 220$ ohms.

Problem 38. — The joint resistance of a number of electromagnets connected in parallel is 8 ohms and the resistance of one magnet is 40 ohms. How many magnets are connected?

By Formula (31) $nq = \frac{R}{J.R.} = \frac{40}{8} = 5$ **electromagnets.**

107. Conductance of a Circuit. — *The conductance of a circuit is the reciprocal of its resistance.* (The reciprocal of a number is the quotient obtained by dividing one by that number, as the reciprocal of 4 is $\frac{1}{4}$; of $\frac{2}{3}$ is $\frac{3}{2} = 1\frac{1}{2}$.) The unit of conductance is the *mho* (ohm spelled backward) A wire of 1 ohm resistance has a conductance of 1 mho; if of 2 ohms resistance, $\frac{1}{2}$ mho; 8 ohms resistance, $\frac{1}{8}$ mho; $\frac{2}{3}$ ohm resistance, $\frac{3}{2}$ or $1\frac{1}{2}$ mhos. The resistance of a circuit is the reciprocal of its conductance. A wire of 7 mhos conductance has $\frac{1}{7}$ ohm resistance.

108. Unequal Resistances in Parallel. – In Fig. 81, two unequal resistances are connected in parallel. The joint resistance will be less than either resistance considered separately.

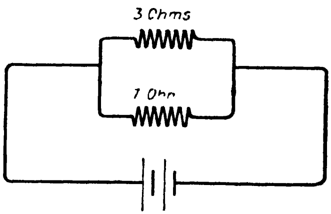


Fig 81. — Two Unequal Resistances in Parallel

TO FIND THE JOINT RESISTANCE OF TWO UNEQUAL RESISTANCES CONNECTED IN PARALLEL:

Divide the product of the resistances by their sum.

Let R = first resistance,
R_1 = second resistance,
J. R. = joint resistance.

Then the joint conductance $= \frac{1}{R} + \frac{1}{R_1} = \frac{R_1 + R}{R \times R_1}$ mhos,

and the joint resistance $= 1 \div \frac{R_1 + R}{R \times R_1}$ ohms,

or $$\text{J. R.} = \frac{R \times R_1}{R + R_1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (33).$$

Problem 39. — Find the joint resistance of two coils in parallel, having a resistance of 3 and 7 ohms respectively (Fig. 81).

By Formula (33) $\quad \text{J. R.} = \frac{R \times R_1}{R + R_1} = \frac{3 \times 7}{3 + 7} = 2.1$ ohms.

IF MORE THAN TWO UNEQUAL RESISTANCES ARE CONNECTED IN PARALLEL:

First find the joint resistance of two resistances, and considering this as a single resistance, combine it with a third resistance, and so on.

109. Conductance Method for Conductors in Parallel.

TO FIND THE JOINT RESISTANCE OF ANY NUMBER OF RESISTANCES CONNECTED IN PARALLEL:

Find the sum of the conductances of the different paths through which the current flows and the joint resistance will be the reciprocal of the sum thus obtained.

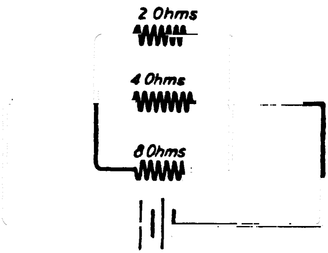


Fig. 82. Three Unequal Resistances in Parallel.

Problem 40.—Find the joint resistance of two coils having 3 and 7 ohms resistance respectively (Fig. 81) by the conductivity method.

By ¶ 107 joint conductance =

$$\frac{1}{3}+\frac{1}{7}=\frac{7+3}{21}=\frac{10}{21}\text{ mho.}$$

$$\text{Joint resistance} = \frac{21}{10} = 2.1\text{ ohms.}$$

Compare with Problem 39.

Problem 41.—Find the joint resistance of three coils of wire having resistances of 2, 4, and 8 ohms respectively (Fig. 82).

$$\text{By ¶ 107 joint conductance } \frac{1}{2}+\frac{1}{4}+\frac{1}{8}=\frac{4+2+1}{8}=\frac{7}{8}\text{ mho.}$$

$$\text{Joint resistance} = \frac{8}{7} = 1.142\text{ ohms.}$$

110. Resistances Joined in Multiple-series.

—WHEN THE RESISTANCES OF ALL THE SERIES GROUPS IN A MULTIPLE-SERIES CIRCUIT ARE THE SAME:

Find the resistance of one group, and divide this sum by the number of groups in parallel.

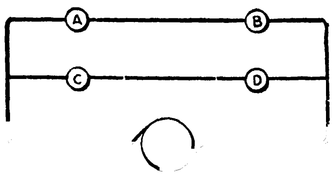


Fig. 83. — Multiple-series Connection of Four Incandescent Lamps.

Let R = resistance of one of like devices (lamp or coil of wire),
ns = number of devices in series in one group,
nq = number of groups in parallel.

$$\text{Total resistance of multiple-series combinations} = \frac{R \times ns}{nq} \quad (34).$$

In Fig. 83, if the resistance R of each lamp is 220 ohms, the total resistance of the lamp combination would equal, by Formula (34), 220 ohms, since there are two groups and two lamps in series in each group.

WHEN THE GROUPS ARE OF UNEQUAL RESISTANCE:

Find the sum of the series resistances in each group, and treating these as single resistances proceed as in ¶ 108 or ¶ 109.

111. Division of Current in a Divided Circuit. — *The division of current in the branches of a multiple circuit is directly proportional to the conductance of the branches, or inversely proportional to their resistance.*

If A and B, Fig. 78, are equal in resistance and a current of 12 amperes flows from the battery, 6 amperes will flow through A, and 6 amperes through B. If A has a higher resistance than B (and consequently a lower conductance), then the greater portion of the current will flow through the lower resistance of B (which has a higher conductance).

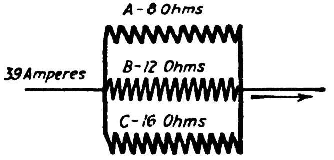


Fig. 84. — Division of Current in the Branches of a Multiple Circuit.

If A has 2 ohms resistance and B 1 ohm, then *twice* as much current will flow through B as through A; or the current is divided into three parts, one-third of which flows through A and two-thirds through B. If the total current is 12 amperes, A then receives 4 amperes and B 8 amperes.

Problem 42. — A current of 39 amperes is passed through three coils of wire joined in multiple, Fig. 84, having the following resistances: A = 8, B = 12, and C = 16 ohms. How many amperes will each coil receive?

The conductance of A is $\frac{1}{8} = \frac{6}{48}$ mho, of B is $\frac{1}{12} = \frac{4}{48}$ mho, and of C is $\frac{1}{16} = \frac{3}{48}$ mho.

By ¶ 109 their joint conductance $= \frac{1}{8} + \frac{1}{12} + \frac{1}{16} = \frac{6+4+3}{48} = \frac{13}{48}$ mho.

Consider the current to divide into 13 parts (6 + 4 + 3), 6 parts of which pass through A, 4 through B, and 3 through C, or directly as their conductances. Then the currents through the various coils are

$$A = \frac{6}{13} \text{ of } 39 = 18 \text{ amperes;}$$

$$B = \frac{4}{13} \text{ of } 39 = 12 \text{ amperes;}$$

$$C = \frac{3}{13} \text{ of } 39 = 9 \text{ amperes.}$$

$$\text{Total current} = 39 \text{ amperes.}$$

112. Ohm's Law Applied to a Battery Circuit. — *When the total E. M. F. is used in Ohm's Law, the total resistance of the circuit must also be used in calculating the current strength.* For example, when an electromagnet of 0.4 ohm is connected to a cell of 2 volts E. M. F. the current through the spool will *not* be E ÷ R or 2 ÷ 0.4 = 5 amperes, as might at first be supposed. It requires a certain portion of the 2 volts to cause the current to flow through the cell's internal resistance. *The internal resistance must be added to the external resistance to obtain the total resistance of the circuit, which total resistance is to be divided into the total pressure to obtain the current strength.* If the internal resistance of the above cell is 0.6 ohm, then the total resistance is 0.4 + 0.6 = 1 ohm, and the current equals E ÷ R = 2 ÷ 1 = 2 amperes, or less than one-half of the former value.

Let R = total external resistance of the circuit in ohms,
r = internal resistance of the battery in ohms.

Then R + r = total resistance of the circuit (external + internal), and Ohm's Law becomes,

$$I = \frac{E}{R + r} \quad \ldots\ldots\ldots\ldots \quad (35).$$

where r represents the internal resistance, in ohms, either of a cell or of the windings of a generator.

Problem 43. — If a bichromate cell, E. M. F. = 2 volts, internal resistance = 0.5 ohm, is connected to an electromagnet having a resistance of 1.5 ohms, what current will the magnet receive?

By Formula (35) $I = \frac{E}{R + r} = \frac{2}{1.5 + 0.5} = 1$ ampere.

Ohm's Law applies *equally as well to any part of a circuit* as to the whole circuit. When applied to part of a circuit, *care*

must be exercised to use the value of the pressure applied to the resistance of that portion of the circuit considered, when E will still represent the volts applied and R the resistance of the part of the circuit to which E is applied. When E is used as the total pressure, R, to correspond, must be the total resistance. When E is used as the pressure applied to part of a circuit, R must be the resistance of that part to which this pressure is applied. This double application of the law is illustrated in Problems 43 to 46, which should be carefully studied.

Problem 44. – The E. M. F. of a cell is 2 volts, its internal resistance is 0.5 ohm. Several different resistance spools are joined *in series* and connected to the cell. By electrical measurement it is found that the pressure causing the current to flow through a 0.4 ohm spool is 0.6 volt. What is the value of the current flowing through this spool? Make a sketch of the circuit.

By Formula (27) $I = \frac{E}{R} = \frac{0.6}{0.4} = 1.5$ amperes.

Since the current is the same in all parts of a *series circuit*, 1.5 amperes must flow through each of the other spools mentioned; also through the internal resistance of the cell. This problem illustrates the difference between E. M. F. and potential difference, see ¶ 35. The difference of potential, or pressure between the spool terminals, is 0.6 volt, while the E. M. F. is 2 volts. In Ohm's Law E may represent either value. See Lesson X.

Problem 45. — What portion of the total E. M. F. in Problem 44 is used in overcoming the internal resistance of the cell?

By Formula (28) $E = I \times R$, from which is derived

$$E = I \times r \quad \ldots\ldots\ldots\ldots \quad \textbf{(36)}.$$

This gives the pressure lost or volts drop inside the cell, ¶ 131.

By Formula (36) $E = I \times r = 1.5 \times 0.5 = 0.75$ volt.

Problem 46. — What portion of the E. M. F. is available for the other spools in the series circuit of Problems 44 and 45?

By Formula (29) total resistance $= \frac{E}{I} = \frac{2}{1.5} = 1.333$ ohms.

Resistance of cell (0.5) plus resistance of one spool (0.4) = 0.9 ohm.
1.333 – 0.9 = 0.433 ohm for balance of spools.

By Formula (28) $E = I \times R = 1.5 \times 0.433 = 0.6495$ volt.

Using Formula (35), $I = \frac{E}{R + r}$, we may also change Formulæ (28) and (29) to include the internal resistance, by replacing R by R + r, thus:

$$E = I \times (R + r) \quad \ldots \ldots \ldots \ldots \quad (37),$$

and

$$(R + r) = \frac{E}{I};$$

by transposition

$$R = \frac{E}{I} - r \quad \ldots \ldots \ldots \ldots \quad (38).$$

Also

$$r = \frac{E}{I} - R \quad \ldots \ldots \ldots \ldots \quad (39).$$

Problem 47. — A cell with an internal resistance of 2 ohms sends a current of 0.035 ampere through the electromagnets of a bell having a resistance of 48 ohms. What is the E. M. F of this cell?

By Formula (37) $E = I \times (R + r) = 0.035 \times (48 + 2) = 0.035 \times 50 = 1.75$ volts.

Problem 48. A current of 0.25 ampere is maintained through a circuit by an E. M. F. of 2 volts; the internal resistance of the cell is 0.5 ohm. What is the value of the external resistance?

By Formula (38) $R = \frac{E}{I} - r = \frac{2}{0.25} - 0.5 = 7.5$ ohms.

QUESTIONS

1. An electromagnet connected to a Leclanché cell attracts many more filings than when it is connected to a Daniell cell. Why?
2. Upon what factors do the E. M. F.'s of batteries and generators depend?
3. An incandescent lamp receives insufficient current to properly illuminate it. Why is this, and what is necessary in order that it may operate at its proper candle-power?
4. Explain Ohm's Law.
5. With a constant resistance, how will the current strength vary with the E. M. F.?
6. With a constant pressure how will the current vary with the resistance?
7. The arc lamps connected to a series generator are joined in series with it. How is the resistance of the circuit affected as additional lamps are inserted in the circuit?
8. A number of incandescent lamps are connected in multiple to a generator. How will the resistance of the circuit be affected if one lamp is turned off?
9. What do you understand by the term *conductance?*

10. An electric heater consists of coils of iron wire through which a current of 2.5 amperes flows, when joined in parallel with an incandescent lamp which receives 1 ampere. Which object possesses the higher resistance? Give proof for answer.

PROBLEMS

1. What pressure must be applied to an incandescent lamp if it has a resistance of 55 ohms and requires 2.2 amperes? *Ans.* 121 volts.

2. A Daniell cell has an E. M. F. of 1 volt and an internal resistance of 2.2 ohms. What current will flow through an electromagnet connected to it, wound with 150 feet of No. 18 B. & S. copper wire? *Ans.* 0.312 ampere.

3. Four hundred incandescent lamps are connected in parallel to a generator circuit. Resistance of the line is 0.5 ohm and the hot resistance of one lamp is 220 ohms. Potential difference at the generator terminals is 112 volts. What current flows through the circuit? Give a sketch. *Ans.* 106.66 amperes.

4. What length of No. 24 B. & S. copper wire would have an equivalent resistance to the joint resistance of 2 lamps connected in parallel? One lamp has a resistance of 110 ohms, the other 33 ohms. *Ans.* 950 feet.

5. Three copper electroplating baths are connected in parallel to a generator which furnishes 117 amperes to them. The resistance of the baths are: No. 1, 24 ohms; No. 2, 36 ohms; No. 3, 48 ohms. What current does each bath receive? Give sketch. *Ans.* 54; 36; 27 amperes.

6. Sketch and name six combinations of 4 incandescent lamps connected to a pair of supply lines. Each lamp has a resistance of 220 ohms (assumed constant) and the potential across the mains is 110 volts. What current will each combination receive? *Ans.* 0.125; 2; 0.5; 0.2; 0.376; 0.676 amperes.

7. In a trolley car, five lamps, each requiring ½ ampere and 100 volts, are connected in series between the line and track across which 500 volts difference of potential is maintained. If 10 such groups are in use what would be the joint resistance of the lamp circuit and how much current would flow from the power station? *Ans.* 100 ohms; 5 amperes.

8. The current through the field magnets of a dynamo is 2 amperes and the applied pressure 120 volts. What is the resistance of the field magnets? *Ans.* 60 ohms.

9. The E. M. F. of a cell is 1.44 volts, its internal resistance 0.16 ohm, and it is connected to a circuit of 0.4 ohm. What pressure is required to send the current used through the battery? *Ans.* 0.41 volt.

LESSON IX

SERIES AND PARALLEL BATTERY CONNECTIONS

113. Methods of Varying Current Strength. — By Ohm's Law, $I = E \div R$, the current through any circuit may be increased in two ways, namely: by increasing the pressure, E (the dividend), or by decreasing the resistance, R (the divisor); by decreasing the pressure, or increasing the resistance, the current will be decreased. For example, 25 volts will cause 5 amperes to flow through 5 ohms. If the pressure is raised to 35 volts the current strength will be 7 amperes. Current from any cell may be *decreased* by inserting resistance in the cell circuit. If sufficient current, however, cannot be obtained from a cell, and as the E. M. F. is a fixed quantity for each type of cell, the E. M. F. may be increased by joining two or more cells in series, so that the total E. M. F. is the sum of the E. M. F.'s of the separate cells. This will be better understood from the hydraulic analogies in ¶ 115.

114. The Size of a Cell. — It has been stated that the E. M. F. of a cell is the same for cells of the same type without regard to size, but that the current depends on the size. In Fig. 85 the cylindrical tank A has a capacity of 100 gallons of water under a pressure of 10 pounds per square inch, due to the weight of the piston. Neglecting the weight of the water, the pressure gauge will record a pressure of 10 pounds. When the valve is opened the water will be discharged at the rate of, say, one gallon per minute, under a pressure of 10 pounds

per square inch, so that at this rate it will require 100 minutes to empty the tank. A similar tank B has a capacity of 10 gallons of water under a pressure of 10 pounds per square inch, due to the piston. Neglecting the weight of the water,

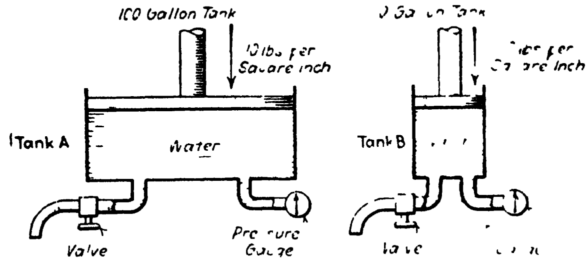


Fig. 85. — Two Cylindrical Tanks of Different Capacities, Containing Water under Pressure

the pressure gauge will record 10 pounds also. The diameter of the pipe is the same size as for tank A, and when this valve is opened the water will flow out at the rate of one gallon per minute under a pressure of 10 pounds per square inch as be-

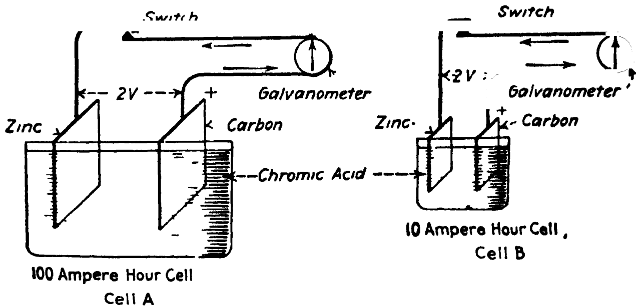


Fig. 86. — Two Cells of Different Size but Having the Same E. M. F

fore, thus requiring only ten minutes to empty tank B. In both tanks the pressure and the rate of flow are the same, but tank A will maintain the current of water ten times as long as tank B.

Now consider Fig. 86, in which the large cell A has a capacity of 100 ampere-hours (see ¶ 94) and an E. M. F. of

2 volts. When the switch is closed the galvanometer indicates, say, 45 divisions deflection, corresponding to a current strength of one ampere, and sufficient chemicals and zinc are present to maintain this current for 100 hours when the pressure is 2 volts and the rate of flow one ampere. Consider now a similar small cell B, which has a capacity of 10 ampere-hours and an E. M. F. of 2 volts. When the switch is closed through the same galvanometer the deflection is 45, as before, corresponding to a current strength of one ampere, sufficient chemicals and zinc being present to maintain this current for only 10 hours when the pressure is 2 volts and the rate of flow one ampere (neglecting the internal resistance). Thus the quantity of electricity depends on the size of the cell. If a large drain pipe had been used in tanks A and B, they would have been emptied more rapidly since the rate of flow would have been greater. If a galvanometer wound with a larger wire had been used, the cells A and B would not have maintained the current for so long a time, the rate of flow, however, being greater.

115. Cells Connected in Series to Increase the E. M. F. — Consider the hydraulic analogy in Fig. 87, where the two similar cylindrical tanks A and B have a capacity of 100 gallons each. The pressure on the water in tank A and connecting pipe is 10 pounds per square inch, due to the weight of the piston, so that the pressure gauge 1 indicates 10 pounds per square inch. In tank B the pressure on the water is 10 pounds per square inch, due to the pressure of the piston on tank A above it, plus 10 pounds per square inch, due to the weight of its own piston, so that gauge 2 will register 20 pounds per square inch. The weight of the water is neglected. When the valve in the drain pipe of tank B is opened this tank will deliver the same quantity of water (100 gallons) as would be delivered by tank B, but at double the pressure. The rate of flow is, therefore, twice as rapid. If a number of similar tanks were connected in like manner above A, the pressure on gauge 2 would be increased 10 pounds per square inch for each tank added, although the quantity of water delivered through the valve would be the same as that of one tank. Consider now Fig. 88, where two cells, each having a capacity

of 100 ampere-hours and an E. M. F. of 2 volts, are joined in series so that the E. M. F.'s are in the same direction. The carbon pole of the first cell is connected to the zinc pole of the second cell, and the two remaining terminals connected to the galvanometer. *Cells connected in this manner are joined in series.* The total pressure applied to the galvanometer when the switch is closed is twice the pressure of one cell (neglecting internal resistance), or 4 volts. The total quantity of electricity that will pass through the galvanometer is the same as would be delivered by each cell separately, 100 ampere-hours, although, since it is delivered at twice the pressure of a single cell, the rate of flow is twice as great as with one cell.

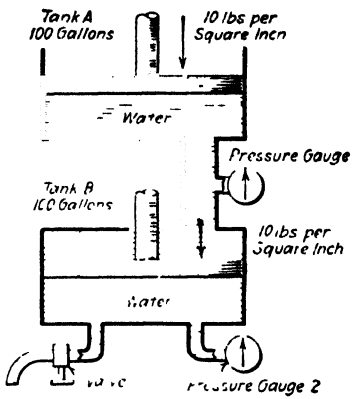


Fig 87. — Two Cylindrical Tanks, Full of Water, Connected in Series for Pressure.

Gauge 2 records twice the pressure indicated upon gauge 1.

When a number of similar cells are thus connected in series the pressure applied to the galvanometer will be increased by 2 volts for each cell so added, but the total quantity of electricity that can be delivered will be equal to the capacity of only one cell.

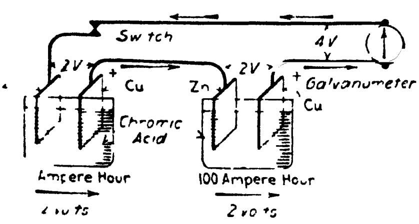


Fig 88. — Two Cells Connected in Series for Pressure.

The galvanometer indicates twice the pressure of one cell

116. Cells Connected in Parallel or Multiple for Quantity. — In Fig. 89 two similar cylindrical tanks have a capacity of 100 gallons of water each, and are connected by a pipe, C, to which a pressure gauge is attached. The piston in each tank exerts

a pressure of 10 pounds per square inch, and the pressure gauge records only 10 pounds pressure, the same as though only one tank were used. The addition of any number of similar tanks will not increase the pressure, which will always remain 10 pounds per square inch. The weight of water is neglected. Although the pressure is not increased, the quantity of water which can be drawn from the valve in the drain pipe increases in proportion to the number of tanks so added; thus, the total capacity of 2 tanks is 200 gallons; 6 tanks, 600 gallons. In Fig. 87 the tanks were arranged in series to add

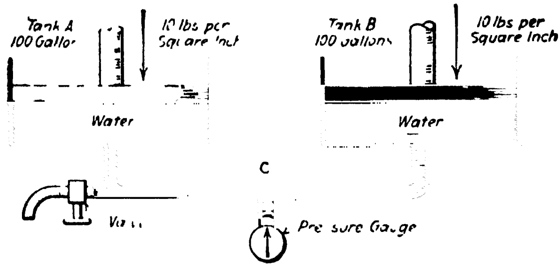


Fig. 89 — Two Cylindrical Tanks, Full of Water, Connected in Parallel for Quantity

The pressure gauge records the pressure due to only one tank, but the quantity of water delivered is equal to the sum of the two capacities

their pressures together, while in this case the tanks are arranged in parallel to add their volumes together.

In a voltaic cell, the output depends upon the amount of zinc to be acted upon. Suppose the cell gives 1 ampere-hour for each square inch of zinc that is exposed to the acid, then by increasing the area of the zinc plates a greater quantity of electricity can be obtained from the cell. This can be done in two ways: by making one very large cell, as B, Fig. 90, or by connecting the like plates of two or more smaller cells, as in A, Fig. 90. Here the zinc plates of two cells are connected by a wire, forming one large zinc plate with double the area, the copper plates being similarly connected. *Cells so connected are arranged in parallel or multiple.* When the switch is closed in arrangement A the galvanometer is subjected to 2 volts pressure, neglecting internal resistance, which pressure would

not be increased, no matter how many cells were thus connected. The total quantity of electricity that will flow through the galvanometer will increase in proportion to the number of cells so added The two cells in A, therefore, could maintain 1 ampere through the galvanometer for 200 hours at a pressure of 2 volts, as could also the larger cell B. The advantage, then, of having small cells is that they can be arranged either for pressure or quantity, as may be desired, by connecting them in series or in multiple.

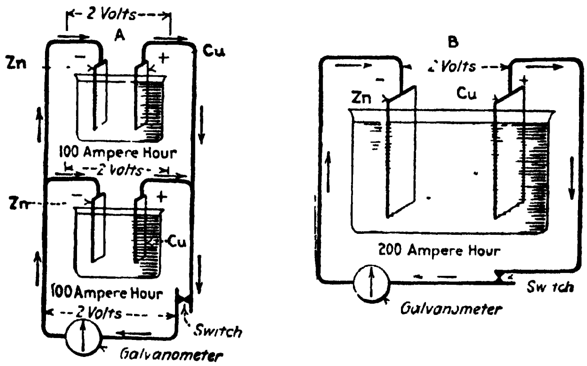


Fig. 90. — Two Cells Connected in Parallel for Quantity.

The total capacity and E. M. F. of the two small cells are exactly equal to the corresponding quantities of the larger cell.

Experiment 47. — Using a galvanometer of high resistance, compare the E. M. F.'s of different types of cells and record the deflections, the value of which will vary as the E. M. F. varies.

Experiment 48. — Connect unlike poles of two similar cells (which is termed joining cells in series) and attach the two remaining terminals to a high-resistance galvanometer. The deflection is greater than with one cell, because the E. M. F.'s of the cells have been added together and a greater pressure is applied to the galvanometer circuit. If the deflections are directly proportional to the current, the value will be nearly doubled. With three similar cells in series the pressure is increased threefold, and so on.

Experiment 49. — Connect two dissimilar cells in series (for example a Daniell cell, 1.1 volts, and Leclanché cell, 1.5 volts) with a high-resistance galvanometer, and the deflection is greater than with either cell alone. The pressure applied to the galvanometer is equal to the sum of the two pressures in series (1.1 + 1.5 = 2.6 volts).

Experiment 50. — Record the deflection produced by one cell (say a Daniell) connected to a high-resistance galvanometer. Using two similar cells, connect the positive poles by one wire, and the negative poles by another wire, and attach lead wires from these junctions to the galvanometer (when like poles are thus connected the cells are joined in *parallel* or *multiple*). The deflection is not perceptibly greater than with one cell, because the E. M. F. of two or more similar cells, joined in parallel, is the same as the E. M. F. of one cell; hence, two Daniell cells of 1 volt each joined in parallel will have a total E. M. F. of 1 volt; 10 such cells in parallel will have a total E. M. F. of 1 volt; 10 such cells in series will have a total E. M. F. of 10 volts. In the above experiments a galvanometer of many turns of fine wire is used, so that little current will flow from the cells, and the deflections represent nearly the true pressures.

117. The Internal Resistance of Cells in Series. — When a number of cells are connected in series, and to an external circuit, the current flowing through the external circuit must

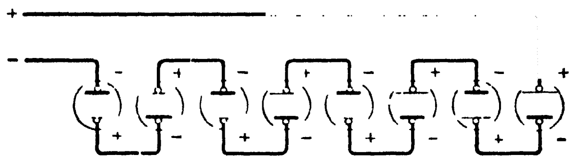


Fig. 91. — Eight Cells Connected in Series for Pressure.

The pressure is eight times that of one cell, as it also the internal resistance.

pass through each cell so connected (Fig. 91), requiring, therefore, a certain fraction of the total E. M. F. to overcome the resistance of each cell.

TO FIND THE TOTAL INTERNAL RESISTANCE OF A NUMBER OF SIMILAR CELLS CONNECTED IN SERIES:

Multiply the resistance of one cell by the number so connected.

Let r = internal resistance of one cell,
ns = number of cells in *series*.

Then

$$\text{total internal resistance of cells in series} = r \times ns \quad (40).$$

Problem 49. — Ten Daniell cells, with an internal resistance of 2 ohms each, are connected in series. What is the total internal resistance?

By Formula (40) total resistance $= r \times ns = 2 \times 10 = 20$ ohms.

118. Current from Cells in Series. — TO FIND THE CURRENT THAT WILL BE MAINTAINED IN AN EXTERNAL CIRCUIT BY A NUMBER OF CELLS IN SERIES:

Find the total E. M. F. applied by multiplying the E. M. F. of one cell by the number connected in series. Find the total internal resistance by Formula (40). Then by Ohm's Law the current equals the total E. M. F. ÷ the total resistance.

Let E = E. M. F. of one cell,
r = internal resistance of one cell,
ns = number of cells in series,
R = external resistance.

Then

$$I = \frac{E \times ns}{(r \times ns) + R} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (41).$$

Problem 50. — Ten Daniell cells are joined in series to two spools of wire in series, one 4 ohms, the other 6 ohms. E. M. F. of each cell is 1 volt, and the internal resistance of each cell is 2 ohms. What current will flow through the circuit?

By Formula (41) $I = \frac{E \times ns}{(r \times ns) + R} = \frac{1 \times 10}{(2 \times 10) + 10} = \frac{10}{30} = \frac{1}{3}$ ampere,
where R = 6 + 4 = 10 ohms.

119. The Internal Resistance of Cells in Parallel or Multiple. — When a number of similar cells are connected in multiple (Fig. 92), and to an external circuit, the total current

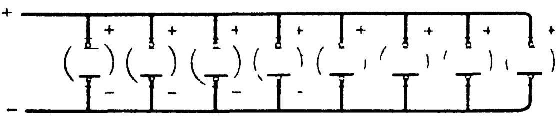


Fig 92. — Eight Cells Connected in Parallel for Quantity.

The pressure is the same as that of one cell; the total internal resistance is one-eighth of that of one cell, the current is nearly eight times that of one cell.

flowing through the external circuit does not pass through the resistance of each cell, as in the series case, but is divided among the cells in proportion to the number in parallel. The internal path for the total current is of much lower resistance than the resistance of one cell. Cells connected in parallel have their like plates connected, Fig. 92, forming practically

one large cell, the positive and negative plates of which are equal in area to the sum of the areas of the respective plates in the separate cells. The area of the conducting liquid is proportionately increased, and consequently, the internal resistance decreased. (See ¶ 72.)

TO FIND THE INTERNAL RESISTANCE OF A NUMBER OF CELLS IN PARALLEL:

Divide the resistance of one cell by the number connected in parallel.

Let r = internal resistance of one cell,

nq = number of cells in multiple or parallel.

Then

$$\text{total internal resistance of cells in parallel} = \frac{r}{nq} \quad . \quad . \quad . \quad \mathbf{(42)}.$$

Problem 51. The cells of Problem 50 are joined in parallel. What is the internal resistance?

By Formula (42) total internal resistance $= \frac{r}{nq} = \frac{2}{10} = \frac{1}{5}$ ohm.

Experiment 51. —Connect a very large Daniell cell to a *low-resistance* galvanometer and record the deflection (say 60 divisions). Now join a much *smaller similar* cell to the same galvanometer and the deflection is much less (say 20). The pressure is the same in both cases, but the internal resistance of the small cell is higher, and since $I = E \div (R + r)$, Formula (35), the current and the deflection must be less. Connect three of the smaller cells in parallel, Fig. 92, and to the galvanometer, and the deflection is now equivalent to that of the single large cell. The pressure is no higher since the cells are in parallel, therefore the total internal resistance of the three cells must be equal to that of the one large cell, since the current and pressure are the same.

120. Current from Cells in Parallel or Multiple. — TO FIND THE CURRENT THAT WILL BE MAINTAINED IN A CIRCUIT BY A NUMBER OF SIMILAR CELLS JOINED IN PARALLEL:

Find the total internal resistance of the cells in parallel by Formula (42). Divide the E. M. F. of one cell by the sum of the external and internal resistances of the circuit.

Let E = E. M. F. of one cell,

r = internal resistance of one cell,

R = total external resistance.

Then $\frac{r}{nq}$ = total internal resistance of the cells in parallel, and the current, according to Ohm's Law, is

$$I = \frac{E}{\frac{r}{nq} + R} \qquad \ldots\ldots\ldots\ldots \quad (43).$$

Problem 52. — Ten Daniell cells are joined in parallel and to an external resistance of 10 ohms. E. M. F. of each cell is 1 volt. Internal resistance of each cell is 2 ohms. Find the current through the external circuit.

By Formula (43) $I = \frac{E}{\frac{r}{nq} + R} = \frac{1}{\frac{2}{10} + 10} = 0.09$ ampere.

By comparison with Problem 50, it will be noted that with this particular external resistance the series arrangement of the cells is much better, as nearly four times the current flows through the circuit when the cells are in series as when connected in multiple.

121. Advantage of Parallel Connection. — Cells are connected in parallel when it is desired to obtain the maximum current through a low external resistance circuit, or when a small current is required for a long period of time. When so grouped the cells are equivalent to one very large cell, and are arranged to give a large quantity of electricity. When connected to a low external resistance, as compared with the internal resistance, the strength of current will also be large, while with a high external resistance the current will be small. The total quantity of electricity available from the supply of the chemicals can thus be used rapidly or slowly, as the conditions may demand. The following problems will illustrate these facts:

Problem 53. — What current will flow through a resistance of 0.1 ohm from a Leclanché or dry cell of 1.4 volts E. M. F. and an internal resistance of 0.4 ohm?

By Formula (35) $I = \frac{E}{R + r} = \frac{1.4}{0.1 + 0.4} = 2.8$ amperes.

Problem 54. — What will be the current in Problem 53 with ten such cells in parallel?

By Formula (43) $I = \frac{E}{\frac{r}{nq} + R} = \frac{1.4}{\frac{0.4}{10} + 0.1} = \frac{1.4}{0.04 + 0.1} = 10$ amperes.

Problem 55. — Suppose the ten cells in Problem 54 are connected in series. What current will flow through the circuit?

By Formula (41) $I = \dfrac{E \times ns}{(r \times ns) + R} = \dfrac{1.4 \times 10}{0.4 \times 10 + 0.1} = \dfrac{14}{4.1} = 3.41$ amperes.

The parallel grouping is therefore preferable in the above problems if the greatest possible current strength is desired in the external circuit.

122. Advantage of Series Connection. — A series grouping is employed when the external resistance is the principal one to be overcome and the maximum current strength is desired in the circuit. The advantage of this method will be shown by the following problems:

Problem 56. — A Leclanché cell, 1.4 volts and internal resistance of 0.4 ohm, is connected to an external resistance of 100 ohms. What current will flow through the circuit?

By Formula (35) $I = \dfrac{E}{R + r} = \dfrac{1.4}{100 + 0.4} = \dfrac{1.4}{100.4} = 0.01394$ ampere.

Problem 57. — Connect ten cells similar to that of Problem 56 in parallel and find the current.

By Formula (43) $I = \dfrac{E}{\dfrac{r}{nq} + R} = \dfrac{1.4}{\dfrac{0.4}{10} + 100} = \dfrac{1.4}{100.04} = 0.01399$ ampere.

Ten cells so connected to this external resistance are, therefore, not much better than one cell.

Problem 58. — Connect the cells of Problem 57 in series and find the current strength.

By Formula (41) $I = \dfrac{E \times ns}{(r \times ns) + R} = \dfrac{1.4 \times 10}{(0.4 \times 10) + 100} = \dfrac{14}{104} = 0.135$ ampere.

With the cells in series, nearly ten times the current is passed through this resistance as when the cells are connected in parallel. In ¶ 121 the multiple combination proved to be best adapted for a particular circuit, while in this case the series grouping is desirable. The student should make a thorough comparison of the problems in ¶¶ 121 and 122.

123. Cells Grouped in Multiple-series. — A combination of the series and multiple grouping of cells is sometimes desirable when a number of cells are available, to give either the maximum current through an external resistance, or to increase the capacity of the cells for maintaining a current in a circuit for a long period of time. For example, 8 volts E. M. F. is required to light a small lamp, and 8 cells are available,

with an E. M. F. of 2 volts each. Arrange one group of 4 cells in series, which will give the desired E. M. F. of 8 volts.[1] Suppose this group would illuminate the lamp for 4 hours. Arrange a second group of 4 cells in series and join this group in multiple with the first group as in Fig. 93. The total E. M. F. is still 8 volts, but with two groups in parallel the quantity of electricity available has been doubled, so that the lamp will now operate for 8 hours. Such a grouping of cells is called a *multiple-series* combination (practically a multiple of series groups). If there were two cells, each having an E. M. F. of 8 volts and an internal resistance of four times one of the above cells, these two could be placed in multiple and substituted for the 8 cells.

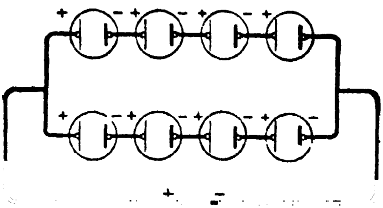


Fig. 93 — Multiple-series Grouping of Cells.

Four cells in series, two groups in parallel. Total E. M. F. equals that of one group, total internal resistance equals one half of that of one group.

TO FIND THE CURRENT FROM A MULTIPLE-SERIES ARRANGEMENT OF CELLS JOINED TO AN EXTERNAL RESISTANCE:

Compute the E. M. F. and internal resistance of one group of cells and consider the results as the data for one "equivalent" cell. Then make calculations for the number of such cells (groups) *arranged in parallel.* See ¶ 125.

124. Internal Resistance of Multiple-series Combination of Cells. —

TO FIND THE INTERNAL RESISTANCE OF ANY MULTIPLE-SERIES COMBINATION OF CELLS:

Multiply the resistance of one cell by the number of cells in one group and divide the product by the number of groups in multiple. The number of cells in each group must be the same, Fig. 93.

Let r = resistance of one cell,

ns = number of cells in series in one group,

nq = number of groups in parallel.

[1] Neglecting the internal resistance.

Total internal resistance of the combination of cells =

$$\frac{r \times ns}{nq} \quad \ldots\ldots\ldots\ldots \quad \textbf{(44).}$$

Problem 59. -- Find the internal resistance of a combination of 24 cells arranged 6 in series, 4 groups in multiple. Each cell has a resistance of 2 ohms.

By Formula (44) Total resistance $= \frac{r \times ns}{nq} = \frac{2 \times 6}{4} = 3$ ohms.

125. Current Strength from Any Combination of Cells.—

TO FIND THE CURRENT THAT WILL BE MAINTAINED IN AN EXTERNAL CIRCUIT BY ANY MULTIPLE-SERIES COMBINATION OF CELLS (Fig. 93):

Divide the total E. M. F. of one series group by the sum of the combined internal and external resistances.

Let I = current in external circuit,
E = E. M. F. of one cell,
ns = number of cells in series in one group,
nq = number of groups in parallel,
r = internal resistance of one cell,
R = external resistance.

Then by Ohm's Law, Formulæ (41) and (44), the current is

$$I = \frac{E \times ns}{\frac{ns \times r}{nq} + R} \quad \ldots\ldots\ldots\ldots \quad (45).$$

Problem 60. -- Find the current that would flow through an electrical device whose resistance is 2 ohms, when connected to 24 cells arranged 4 in series and 6 in parallel. Each cell has an E. M. F. of 2 volts and an internal resistance of 3 ohms.

E = 2 volts, ns = 4 cells in one group, r = 3 ohms, nq = 6 groups in parallel, R = 2 ohms.

By Formula (45) $I = \frac{E \times ns}{\frac{ns \times r}{nq} + R} = \frac{2 \times 4}{\frac{4 \times 3}{6} + 2} = \frac{8}{4} = 2$ amperes.

TO FIND THE CURRENT THAT WILL BE MAINTAINED IN AN EXTERNAL CIRCUIT FROM ANY SERIES-MULTIPLE COMBINATION OF CELLS (Fig. 94):

Find the internal resistance of one multiple group by Formula (42), and consider the result as the data for one "equivalent" cell (group). Calculate the total E. M. F. and resistance for the multiple groups in series and determine the current by Ohm's Law.

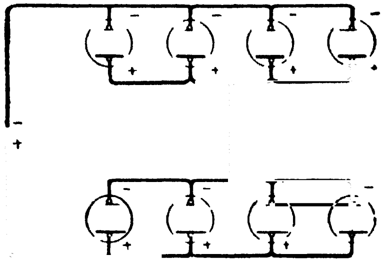


Fig. 94. — Series-multiple Grouping of Cells.

Four cells in parallel, two groups in series, equivalent to two cells in series and four groups in parallel

Problem 61. — A series-multiple combination of 8 cells is joined to an external resistance of 3 ohms. The cells are arranged 4 in parallel, 2 groups in series (Fig. 94). Each cell has an E. M. F. of 2 volts and an internal resistance of 0.5 ohm. What current will flow through the external circuit?

E. M. F. of 1 group = 2 volts.

E. M. F. of 2 groups in series = 2 × 2 = 4 volts.

By Formula (42) internal resistance of 1 group $= \frac{r}{nq} = \frac{0.5}{4} = 0.125$ ohm.

By Formula (40) internal resistance of 2 groups in series = r × ns = 0.125 × 2 = 0.25 ohm.

By Formula (35) $I = \frac{E}{R + r} = \frac{4}{3 + 0.25} = 1.23$ amperes.

126. Cells in Opposition. — When two cells are joined in parallel their E. M. F.'s are in opposition, since each one tends to send a current through the other. If the E. M. F.'s are equal no current will flow through the connecting wires. Two equal forces, acting in direct opposition, produce equilibrium; if, however, the forces are unequal, then motion is produced in the direction of the greater force. For example, if the pressure acting downward on each piston in tanks A and B, Fig. 89, is the same, no water will flow through the connecting pipe. Suppose the total downward pressure on A is 10 pounds per square inch and on B 30 pounds per square inch, then a current of water will flow from B to A, due to the difference in pressure between the opposing forces, 30 − 10 = 20 pounds per square inch. The piston at A will move upward. When

two cells of unequal E. M. F.'s are connected in opposition a current will flow through the connecting wires and internal resistance in the direction dictated by the higher E. M. F.

TO FIND THE CURRENT IN ANY CIRCUIT WHEN THE E. M. F.'S ARE IN OPPOSITION:

Divide the difference between the E. M. F.'s by the sum of the external and internal resistances.

The opposing E. M. F. is called the *Counter E. M. F.* and is usually represented by $\mathcal{E}$. Formula (35), $I = \frac{E}{R + r}$, may include the above statement when expressed thus:

$$I = \frac{E - \mathcal{E}}{R + r}.$$

Problem 62. — Four Daniell cells, each having an E. M. F. of 1 volt and an internal resistance of 1.2 ohms, are connected in series and in opposition to an accumulator having an E. M. F. of 2 volts and an internal resistance of 0.05 ohm. The resistance of the connecting wire is 0.2 ohm. What is the charging current?

E. M. F. $= 1 \times 4 = 4$ volts, $\mathcal{E} = 2$ volts, $r = 1.2 \times 4 + 0.05 = 4.85$ ohms, $R = 0.2$ ohm.

By above Formula $I = \frac{E - \mathcal{E}}{R + r} = \frac{4 - 2}{0.2 + 4.85} = 0.4$ ampere.

QUESTIONS

1. According to Ohm's Law how may the current through any circuit be regulated?
2. What is the advantage of a large cell over a small one of the same type?
3. If you were given the choice of two small Daniell cells or one large Daniell cell of twice the capacity of the small ones, which would you prefer? Why?
4. Why are cells connected in series?
5. Why are cells connected in parallel?
6. How would the resistance of a battery having four cells connected in series, compare with the resistance of the battery if the four cells were connected in parallel?
7. What is the advantage of a series connection of cells? What is the advantage of a parallel connection of cells?

8. What advantage is there in grouping a number of cells in a multiple-series connection?

9. Would you connect two cells having an E. M. F. of 0.7 and 2.4 volts respectively in series? Would you connect these cells in parallel? Give reason for your answers.

10. Derive an equation for the current maintained in a circuit by a *series-multiple* combination of cells.

PROBLEMS

1. A bell circuit is operated by 3 dry cells in series. Each cell has an E. M. F. of 1.4 volts, and an internal resistance of 0.4 ohm. What current will the bell receive if its resistance, including the line, is 20 ohms? *Ans.* 0.198 ampere.

2. To operate a small motor 6 Grenet cells are connected in parallel. Each cell has an E. M. F. of 2 volts and an internal resistance of 0.6 ohm. The total external resistance is 0.9 ohm. What current will the motor receive? *Ans.* 2 amperes.

3. Some miniature incandescent lamps are lighted by 24 Edison-Lalande cells, arranged 4 in series and 6 groups in parallel. Each cell has an E. M. F. of 0.7 volt and an internal resistance of 0.15 ohm, and the external circuit has a resistance of 0.21 ohm. What current do the lamps receive? *Ans.* 9 amperes.

4. Four Leclanché cells, E. M. F. of 1.4 volts each, and internal resistance of 0.4 ohm each, are to send a maximum current through a circuit of 15 ohms resistance. Would you connect the cells in series or in parallel? Determine the maximum current. *Ans.* 0.337 ampere.

5. Calculate the current from all symmetrical combinations of 6 cells connected to an external resistance of 2 ohms. Each cell has an E. M. F. of 1.4 volts and an internal resistance of 0.5 ohm. *Ans.* Series = 1.68 amperes; parallel = 0.67 ampere; 2 in series, 3 groups in parallel = 1.2 amperes; 3 in series, 2 groups in parallel = 1.52 amperes.

6. A Grenet cell (E. M. F. 2.3 volts, internal resistance 0.2 ohm) and a dry cell (1.5 volts and 0.6 ohm internal resistance) are connected in parallel. What current will flow through the connecting wire? *Ans.* 1 ampere.

7. A Daniell cell, Grenet cell, and Leclanché cell having E. M. F.'s of 1.1, 2.0, and 1.4 volts and internal resistances of 2.0, 0.3, and 0.5 ohms respectively, are connected in series to a resistance of 3 ohms. What current flows through the external resistance? *Ans.* 0.77 ampere.

8. Eight cells are joined in series-multiple; 4 cells in multiple, 2 groups in series, Fig. 94. Each cell has an E. M. F. of 2 volts and an internal resistance of 0.5 ohm. The cells are connected to a small incandescent lamp having a hot resistance of 0.75 ohm. What current will the lamp receive? *Ans.* 4 amperes.

LESSON X

PRACTICAL APPLICATION OF OHM'S LAW

Electromotive Force and Potential Difference — Hydraulic Analogy to Illustrate Volts Lost — Measurement of Electric Pressure — Potential Difference, Current and Resistance of Parallel or Divided Circuits — Volts Lost in an Electric Circuit — Distribution of Potential in a Circuit — Volts Drop in Wiring Leads — Variation of Potential Difference with Variation of External Resistance — Table IX — Questions and Problems.

127. Electromotive Force and Potential Difference. — *Volts lost or volts drop in a Circuit.* — Electromotive force is the total force generated; potential difference is any part of the total E. M. F. The E. M. F. of any generator is not available for use in the external circuit, since part of it is required to cause the current to flow through the internal resistance of the generator (battery or dynamo). By the expressions *fall of potential*, *drop* or *volts lost* in any part of a circuit is meant that portion of the E. M. F. which is used in causing the current to flow between the two points considered. For example, the "voltage drop" across a lamp means the potential difference across the lamp terminals; it is the force which is causing the current to flow through the lamp. Two "volts lost on the line" means that this much pressure is lost or used in sending the current through the line. The E. M. F. is the sum of all the potential differences, as, the drop on the line plus the drop across the lamp plus the drop on the internal resistance of the generator. The term *volts lost* or *volts drop* implies that energy is lost, since electric power is the product of volts and amperes, Formula (54); pressure could not be "lost" in any circuit unless a current had been transmitted by it.

128. Hydraulic Analogy to Illustrate Volts Lost. — A hydraulic analogy may assist somewhat in understanding the fall of potential or volts drop in an electric circuit. In Fig. 95, T is a cylindrical tank filled with water under pressure due to

the weight of the piston P, and AB is a pipe for transmitting the water to point B. With the valve at B closed the pipe is full of water, but there is no current through it. The gauges at A and B each indicate 60 pounds per square inch, which represents the water-motive-force or power to move the water. When the valve is opened half on and a current of water is passed through the pipe, the pressure on the gauge at A is still 60 pounds[1] while at B it is only 50 pounds. The weight of water is neglected. There is thus a difference in pressure of 10 pounds between the two points A and B, and this force has been used or lost in overcoming the friction or resistance

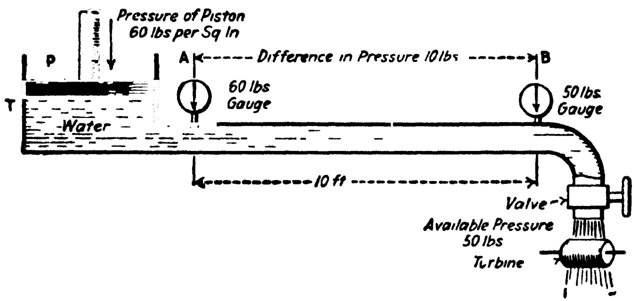


Fig. 95 — Tank of Water and Transmission Pipe to Illustrate the Fall of Potential.

offered by the inner surface of the pipe to the running water. The available pressure at the B end of the pipe, which might be used for driving a turbine, is only 50 pounds, while the total pressure is 60 pounds. There is thus not a loss of quantity of water, but a loss of energy, as work has been performed in moving the water. Suppose the pipe to be of uniform bore and 10 feet long, then a gauge inserted at a point one foot from A would indicate 59 pounds; at two feet, 58 pounds, etc.; or there is a gradual fall or drop of pressure along the pipe which is directly proportional to the length when the resistance is uniform, or a drop or "loss of head" of one pound per foot in length.

[1] The term "pound" is used as an abbreviation of the pressure unit "pound per square inch."

The difference in pressure between any two points is the pressure required to send the current between these points, and is found by subtracting the pressure of that gauge which is more distant from the generating source, from the pressure of the gauge nearer to it. The valve is now fully opened and the gauge at A still indicates 60 pounds, while that at B now indicates 40 pounds. A difference in pressure of 20 pounds is required to cause the increased current to flow through the pipe, leaving only 40 pounds available pressure to be applied to the turbine at B. A force of two pounds is required

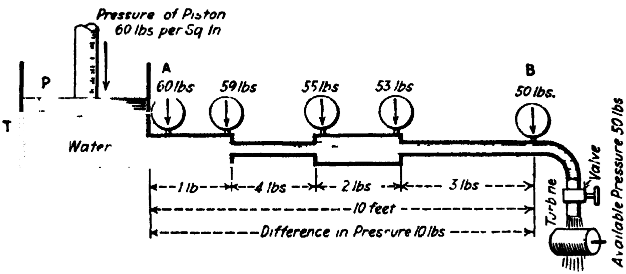


Fig 96. — Hydraulic Analogy of the Fall of Potential.

to send the increased current through each foot of the pipe, and the sum of the pressures lost in the 10 feet equals 20 pounds, or the difference in pressure between the points A and B. If the transmitting pipe considered above is replaced by one much larger in diameter, the resistance will be less, and less pressure therefore will be lost in transmitting the water. so that a greater available pressure will result.

Suppose that the pipe AB is composed of several pieces of different sizes joined as in Fig. 96; with no current flowing the pressure at gauge B is equal to that at A. With the valve opened half on, gauge A indicates 60 pounds and gauge B 50 pounds, as before, making a loss in pressure between the two points A and B of 10 pounds, which causes the current to flow between them. While the current of water may be the same as before and the total pressure lost also the same, the distribution of the lost pressure is not the same, since the resistance of the pipe is not uniform, it being practically a number of

pipes of different sizes, and therefore of different resistances, connected in series. The greatest difference in pressure will be between points having the greatest resistance, such as the length of pipe of small diameter, where four pounds are required to send the current of water through this section of the pipe, while only two pounds are required to send the same current through the larger adjacent section. The opposition to be overcome in the pipe of smaller diameter is twice as great as in the larger pipe, since twice the pressure is required to send the *same* current through it. In hydraulics, calculations are made to deliver water at a certain rate of flow and under a certain pressure, in which case the pressure and energy lost in transmitting the water must be considered. The same is true in calculating the sizes of pipes for gas lighting, and of wires for carrying electric currents, ¶ 218.

129. Measurement of Electric Pressure. — To measure electric pressure (volts) between two points requires galva-

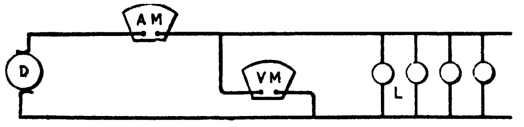


Fig. 97. — Connection of a Voltmeter and an Ammeter to a Circuit.

nometers of very high resistance, and when properly calibrated their scales are graduated directly in volts and the instruments are then termed *voltmeters*, ¶ 218.

Voltmeters are connected directly across the line, the voltage of which is required, or in parallel with the conductor between the ends of which the P. D. is required. *A voltmeter is never connected in series with the line,* and an *ammeter never across or in parallel with the line,* but always in series with it (see Fig 97). Figs. 98, 101 to 107 illustrate the proper connections for measuring the potential differences in the various parts of a circuit.

Experiments 52 and 53 that follow illustrate the use of a voltmeter for measuring the voltage across the parts of a circuit; the experiments also prove that the voltage across any part of a series circuit is proportional to the resistance of that

part. The *current* value in any part of a series circuit is always the same.

Experiment 52. — Four spools of wire, A, B, C, and D, Fig. 98, with resistances of 2, 3, 4, and 6 ohms respectively, are connected in series and to a battery. The spools may represent lamps, magnets, or any other electrical devices. When the battery circuit is closed through the above circuit, and the voltmeter connected directly across its terminals, 30 volts potential difference is indicated. The total external resistance is 2 + 3 + 4 + 6 = 15 ohms, and the 30 volts potential difference indicated by the voltmeter is the pressure causing the current to flow through this external resistance. The current is, by Formula (27), 30 ÷ 15 = 2 amperes.

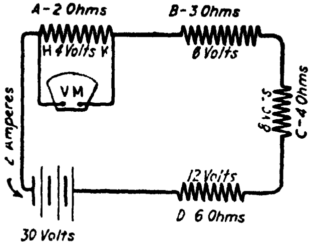


Fig. 98. — Measuring the Voltage Drop in an Electric Circuit.

To measure the proportion of the total P. D., 30 volts, causing the current to pass through the 2-ohm spool, A, Fig. 98, the voltmeter is placed in parallel with it, or connected to the points H and K, and indicates 4 volts. When the voltmeter is connected across the 3-ohm spool B, 6 volts are indicated. The current is the same as through spool A, the resistance, however, being $1\frac{1}{2}$ times as great as A requires also $1\frac{1}{2}$ times the voltage that A requires. Spool C has 4 ohms, or twice the resistance of A, and the voltmeter indicates 8 volts.

By Formula (28) the voltage required to send 2 amperes through 4 ohms is calculated to be E = I × R = 2 × 4 = 8 volts; also in spool A the calculated voltage is 4 volts. The results of the measurements across the four spools by a voltmeter are indicated in Fig. 98, the sum of the volts drop on all the spools is 4 + 6 + 8 + 12 = 30 volts, or the potential difference measured at the battery. The total external resistance is 15 ohms, the current 2 amperes, and by Formula (28) the potential difference equals I × R = 2 × 15 = 30 volts. Suppose the internal resistance of the cells, r, is 5 ohms, then E = I × r or 2 × 5 = 10 volts drop in the cells.

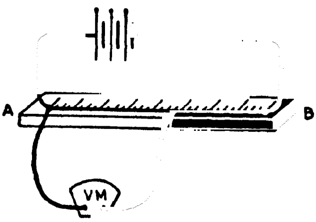


Fig. 99. — Fall of Potential along a Wire.

If the voltmeter is connected across the battery it indicates the P. D. of 30 volts, when 2 amperes are flowing. If the external circuit is now opened the voltmeter indicates the E. M. F. of the cells, which is the sum of all the former potential differences in the circuit or 30 + 10 = 40 volts E. M. F.

Experiment 53. — In Fig. 99, a fine German silver wire, AB, uniform in size, is stretched on a board between binding posts and a scale of inches arranged directly beside it. The wire is connected in circuit with one or more cells, preferably of the Daniell type, so that the current flowing through the wire will be constant. If the terminals of a galvanometer or voltmeter are held on the wire, so as to include a portion of its length between them, as in Fig. 99, the potential difference between the points embraced will be represented by the value of the deflection. One terminal may be fixed at point A and the other terminal gradually moved along the wire toward B. The deflection increases in approaching B For example, with six inches of wire between voltmeter terminals the drop is 0.4 volt; 12 inches, 0.8 volt, etc.

Since the current is the same in all parts of the circuit, the same deflection will be produced for equal distances on the wire, provided its resistance is uniform. If a copper wire of the same size is connected in series with the German silver, the volts drop on 12 inches of copper will about equal the drop on 1 inch of German silver, since the latter has about twelve times the resistance of copper, and to send the same current through it, therefore, requires twelve times the pressure. The student should make a table of comparative lengths and deflections for several different wires of the same diameter joined in series, as the following:

Inches	Copper	German silver	Iron
	Deflection	Deflection	Deflection
5 10 15 Etc.			

130. Potential Difference, Current and Resistance of Parallel or Divided Circuits. — The potential across each branch of a parallel circuit is the same as the voltage between the points where the branches divide and where they again unite. In Fig. 100 the voltage across resistance A is the same as the voltage across the combination A and B since they are both connected between the same points, X and Y. The total current in a parallel combination equals the sum of the currents

in the several branches; in Fig. 100 the current flowing from X to Y equals the current in A plus the current in B.

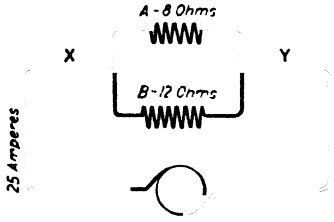


Fig. 100. — Finding the Currents through the Branches of a Divided Circuit.

TO FIND THE POTENTIAL DIFFERENCE TO BE MAINTAINED BETWEEN THE POINTS WHERE SEVERAL CIRCUITS BRANCH AND WHERE THEY AGAIN UNITE:

Multiply the sum of the currents in all the branches by the joint resistance of the branches.

Let I_1, I_2, etc. = currents in the branches,

E = potential difference across branches,

J. R. = joint resistance of the branches.

Then

$$E = (I_1 + I_2 + \text{etc.}) \times J.\ R. \qquad \textbf{(46)}.$$

Problem 63. — Two coils A and B, having resistances of 8 and 12 ohms respectively, are connected in parallel (Fig. 100). Find the potential difference required to send 15 amperes through A and 10 amperes through B.

By ¶ 109 joint conductance $= \frac{1}{8} + \frac{1}{12} = \frac{3+2}{24} = \frac{5}{24}$ mho.

Joint resistance $= \frac{24}{5} = 4.8$ ohms.

By Formula (46) $E = (I_1 + I_2) \times J.\ R. = (15 + 10) \times 4.8 = 120$ volts.

TO FIND THE CURRENT IN ANY BRANCH OF A PARALLEL CIRCUIT:

Divide the potential difference between the points where the branches divide and unite by the resistance of that branch.

Problem 64. — Find the current through each branch of the divided circuit in Fig. 100, if the potential difference is 24 volts.

By the above statement the current in A is $I = \frac{E}{R} = \frac{24}{8} = 3$ amperes, and the current in B is $\frac{24}{12} = 2$ amperes.

The joint resistance of a parallel combination can generally be found by a direct application of Ohm's Law as well as by

the method of ¶ 109, although the conductance method is sometimes more convenient.

The separate resistance of any branch of a multiple circuit may be found by dividing the potential difference across the branch by the current flowing through that branch, according to Ohm's Law.

131. Volts Lost in an Electric Circuit. — Consider now an electric circuit in which a generator (battery or dynamo) is supposed to maintain a constant pressure of 60 volts between two parallel lines at the point A, Fig. 101, as indicated by a high-resistance galvanometer or voltmeter. With no current flowing from the generator the voltmeter will indicate 60 volts at point B (neglecting the pressure used to transmit the small current used by the voltmeter). By closing the switch at the right, the lamp L is lighted, and the ammeter indicates 1 ampere flowing through the circuit. The voltmeter at A still indicates 60 volts, but the voltmeter at B only 50 volts. There is, therefore, a difference in pressure between points A and B of 10 volts, which is used in overcoming the resistance of the line and causing the one ampere to flow through it. The available pressure at point B to perform useful work in the lamp is, therefore, only 50 volts and causes one ampere to flow through it. There is no loss of current but a loss of energy on the line, that is, work has been performed in transmitting the current from A to B, just as in the case of the water in the pipe line of ¶ 128.[1] If 10 volts are required to send one ampere through the line its resistance, by Formula (29), will be 10 ohms.

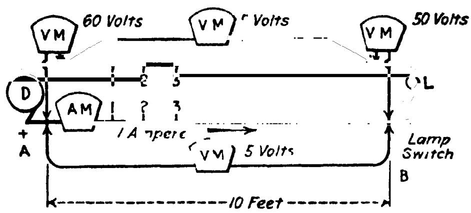


Fig. 101. — Volts Drop in an Electric Circuit.

If the wire is of uniform area and 10 feet in length from A to B, the voltmeter will indicate 59 volts when placed across the line at points 1–1, one foot distant from A; 58 volts at 2

[1] See also Lesson XI.

feet, or points 2–2, etc.; or the fall of potential along the line is directly proportional to its length and resistance. Since the total resistance of the line is 10 ohms, the resistance of one wire is 5 ohms and the difference in potential required to send one ampere through 5 ohms is $E = I \times R = 1 \times 5 = 5$ volts. A voltmeter placed across one side of the line to include 10 feet of its length will indicate a potential difference of 5 volts drop on this side, and the same drop will occur on the other side of the line. Since there are 5 volts drop on 10 feet of wire of uniform resistance the drop per foot will be ½ volt, or 1 volt for every 2 feet, etc. The voltmeter, when placed in parallel with any length of the wire, will indicate the difference of potential between the points included.

Now turn on the switch of a second lamp of the same resistance, the ammeter will now indicate 2 amperes (Fig. 102). The voltmeter at A still indicates 60 volts as before, but that at B now indicates only 40 volts. The difference in pressure between points A and B is 20 volts, since twice the current through the same resistance requires double the pressure to be applied. The available pressure applied to the lamps is 40 volts. If the wires considered above were just double the area, only one half of the pressure would be lost on the leads, and therefore one half of the energy would be lost, and a higher P. D. at point B would be maintained.

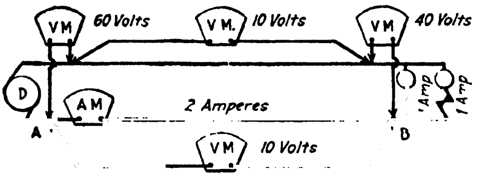


Fig. 102. — Volts Drop in an Electric Circuit.

Suppose the transmitting line to be composed of several wires of different sizes connected in series as represented by the heavy and thin lines in Fig. 103. With one lamp connected at B, the voltmeter may read 50 volts, as before, but the fall of potential or drop on the line of 10 volts will not now be uniform, since the resistance is not uniform. The greatest potential difference or drop will be between the points of highest resistance. Consider the equal lengths of wire E F and F G

of *unequal areas*. The *current* is the *same* through each, but the voltmeter indicates 3 volts when connected across points E F, and only 1 volt when placed across points F G. The thin wire E F has three times the resistance of the wire F G, since three times the pressure is required to send the same current through it. The drop in volts in other portions of the line may be measured in the same manner, the sum of all the readings being equal to the total loss on the line, or 10 volts.

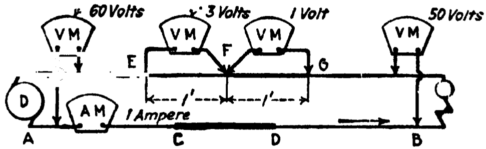


Fig. 103. — Drop in a Non-uniform Electric Circuit.

132. Distribution of Potential in a Circuit. — In the foregoing illustrations the pressure was assumed to be maintained constant at point A. Consider now a battery or generator D, Fig. 104, with an internal resistance (r) of 4 ohms, connected to one lamp at B, 10 feet distant from A. The voltmeter at

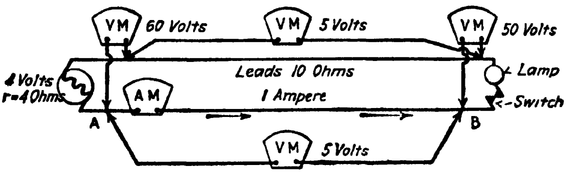


Fig. 104. — E. M. F. and Potential Difference in an Electric Circuit.

A indicates 60 volts as before, and with one ampere flowing through the lamp, 50 volts at B. Ten volts are required to send one ampere through the lead wires, and since the internal resistance of the generator is 4 ohms, 4 volts will be required to send one ampere through it, Formula (28). The total pressure or E. M. F. is, therefore, 4 + 10 + 50 or 64 volts. The voltmeter across the generator terminals, however, indicates the potential difference or that portion of the E. M. F. available in the external circuit, 60 volts. If the lamp at B is turned off the voltmeters at both points A and B will indicate 64 volts, or the E. M. F. of the source of electricity. Now

connect two lamps in circuit, Fig. 105; the resistance of one lamp is 50 ohms, and of two in parallel is 25 ohms, Formula (30). The total resistance of the circuit is R + r = 10 + 25 + 4 = 39 ohms, and the current, therefore, equals 64 ÷ 39 or 1.64 amperes, Formula (27). The voltmeter at B indicates 1.64 × 25 = 41 volts, Formula (28), while the voltmeter at A indicates 1.64 × (10 + 25) = 57.4 volts potential difference at the generator terminals. The drop on the internal resistance is 4 × 1.64 = 6.56 volts. Total E. M. F. is 6.56 + 57.4 = 64 volts (nearly). If the lamps require 50 volts to send sufficient current through them to give the proper amount of light, with 40 volts across their terminals they will now burn dimly,

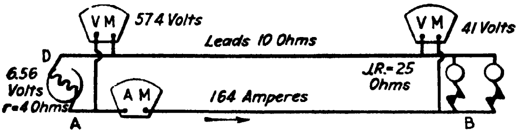


Fig. 105. - E. M. F. and Potential Difference in an Electric Circuit.

since each lamp does not receive one ampere, as before. The total E. M. F. must be increased, say by adding more cells in series, or increasing the field strength of the generator, if 50 volts are to be maintained across the two lamps in parallel. If one lamp is then turned out the other lamp receives a greater pressure than 50 volts, since the drop on the leads and internal resistance is less when the current through them is diminished. The E. M. F. must therefore be decreased as the current is decreased and increased when the current increases. In a battery installation for lighting lamps a special switch is used to connect or disconnect several end cells, as the voltage regulation may require. This switch is called an *end-cell switch.*

In ¶¶ 131 and 132, the resistance of the leads has been considerably exaggerated, and consequently also the volts drop, in order to emphasize the effects. In practice the drop on commercial lighting and power circuits is much less (see ¶ 255), so that the voltage will not change widely with variations of load

Problem 65. — Eight arc lamps are connected in series to a series generator, Fig. 106; each lamp requires 45 volts and 10 amperes. The resistance of the series field is 4.5 ohms and the armature has a resis-

tance of 4.5 ohms. (a) What pressure will be indicated by a voltmeter placed across the brushes? (b) What is the E. M. F. of the generator?

By Formula (29) $R = \frac{E}{I} = \frac{45}{10} = 4.5$ ohms per lamp.

Resistance of 8 lamps in series $= 8 \times 4.5 = 36$ ohms.

By Formula (28) $E = I \times R = 10 \times 36 = 360$ volts potential difference (a).

Total resistance $r + R = 4.5 + 4.5 + 36 = 45$ ohms.

By Formula (37) $E = I \times (R + r) = 10 \times 45 = 450$ volts (b).

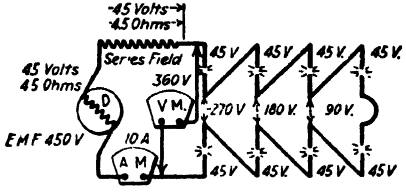


Fig. 106.—E. M. F. and Potential Difference in a Series Arc-light Circuit.

133. Volts Drop in Wiring Leads. — The size of wire required to conduct a given current a certain distance may be readily obtained by finding its resistance by Ohm's Law. In Fig. 107 a generator, D, is supplying current, 20 amperes, to a number of lamps, L, located at a distance of 100 feet. The voltage at the generator is 112 volts and at the lamps is 110 volts. There are 2 volts drop on the line, or two volts are required to send 20 amperes through the 200 feet of copper wire. By Formula (29) the resistance of the line equals $E \div I = 2 \div 20 = 0.1$ ohm per 200 feet, or 0.5 ohm per 1000 feet. From the wire table, on page 67, is found the nearest size of wire corresponding to 0.5 ohm per 1000 feet, which is a No. 7 B. & S. gage.

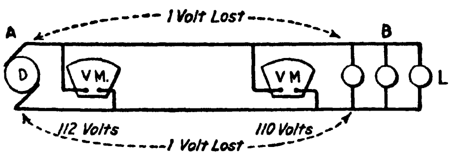


Fig. 107. — Volts Lost in Wiring Leads.

As a check upon this calculation the table of carrying capacities, ¶ 236, should be consulted to further ascertain whether the wire is large enough to carry the current without undue temperature rise.

134. Variation of Potential Difference with Variation of External Resistance. —

Experiment 54. — Connect a voltmeter to a Grenet cell and also a variable resistance, R, in series with an ammeter, Fig. 108. With switch

S open, the voltmeter indicates 2 volts or the E. M. F. of the cell. Adjust arm A of the rheostat so that a high resistance will be connected to the cell, say 100 ohms, when switch S is closed. The voltmeter now indicates 1.999 volts, or the potential difference is nearly equal to the E. M. F. when the external resistance is high, since very little current flows. Now reduce R to about 9.6 ohms; if the cell's resistance = 0.4 ohm, r + R = 10 ohms and the current = 0.2 ampere. The voltmeter indicates I × R = 0.2 × 9.6 = 1.92 volts potential difference which is causing 0.2 ampere to flow through 9.6 ohms; the remaining 0.08 volt is required to send the same current through the internal resistance. Reduce the external R to 0.4 ohm and the voltmeter indicates 1 volt P. D. Since the external resistance is now equal to the internal resistance there is 1 volt drop inside the cell. Short-circuit the cell by a very low resistance and the voltmeter indicates practically zero, the current from the cell is a maximum and all of the E. M. F., 2 volts, is used in sending the current through the cell's internal resistance. The preceding experiments may be summed up in the following table, which can be verified by the apparatus in Fig. 108:

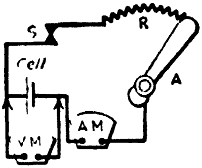


Fig. 108. — Variation of P. D. and Current with a Variation of Resistance.

Table IX. Variation of Current, Pressure and Resistance

Ohms External Circuit, R	Volts across Battery, P. D.	Amperes, I
Infinity	Equal to E. M. F.	0
Great compared with r	Very little less than E. M. F.	Small
Any value	$\frac{R}{R + r} \times$ E. M. F.	$\frac{E. M. F.}{R + r}$
Small compared with r	Small	Large
0	0	Maximum and equal to $\frac{E. M. F.}{r}$

The following formulæ derived from Ohm's Law will be found useful in calculating the internal resistance and potential difference:

Let E = E. M. F. in volts,
P. D. = potential difference in volts,
R = resistance of external circuit in ohms,
r = internal resistance in ohms.

Then the current by Formula (35) is

$$I = \frac{E}{R + r}.$$

Also

$$I = \frac{P.\,D.}{R}.$$

By combining the first and second equations we get,

$$\frac{P.\,D.}{R} = \frac{E}{R + r},$$

or

$$P.\,D. = \frac{R \times E}{R + r} \quad \ldots\ldots\ldots \quad (47).$$

Eliminating R from the first and second equations, there results

$$\frac{E - Ir}{I} = \frac{P.\,D.}{I},$$

from which

$$I = \frac{E - P.\,D.}{r}, \quad \ldots\ldots\ldots \quad (48).$$

or

$$r = \frac{E - P.\,D.}{I} \quad \ldots\ldots\ldots \quad (49).$$

By Formula (49) a cell's internal resistance may be measured by noting the voltmeter and ammeter readings when it is connected, as in Fig. 108.

Problem 66. — The E. M. F. of a Leclanché cell is 1.4 volts, and its P. D. measured at the battery terminals when 0.8 ampere is flowing is 1 volt. What is the cell's internal resistance?

By Formula (49) $r = \frac{E - P.\,D.}{I} = \frac{1.4 - 1}{0.8} = \frac{1}{2}$ ohm.

Problem 67. — The E. M. F. of a generator is 112 volts; the resistance of its circuit is 5 ohms; the resistance of the generator armature is 0.05 ohm. What P. D. will a voltmeter indicate when placed across the brushes?

By Formula (47) $P.\,D. = \frac{R \times E}{R + r} = \frac{5 \times 112}{5 + 0.05} = 110.8$ volts.

QUESTIONS

1. Distinguish between E. M. F. and potential difference.
2. What do you understand by the term "drop" or "volts lost"?
3. Make a sketch of an electric circuit, showing how you would place

an ammeter in the circuit to read the current; also a voltmeter to read the potential difference of the circuit.

4. The E. M. F. of a cell measured by a voltmeter is 1.8 volts. When connected to a spool of wire the voltmeter across the battery terminals indicates only 0.7 volt. Account for the volts lost, and state what pressure is applied to the spool.

5. Four coils of wire having resistances of 1000, 100, 10, and 1 ohms respectively are successively connected to a battery of 10 volts E. M. F. What will be the comparative value of the readings of a voltmeter placed across the terminals as compared with the E. M. F.? State also the comparative current strength in each case.

PROBLEMS

1. Find the size of wire required to conduct current to 100 220-ohm lamps in parallel, located at a distance of 125 feet from the generator, which maintains a constant pressure of 112 volts at its terminals. The lamps should receive 110 volts. *Ans.* No. 2 B. & S.

2. What P. D. must be maintained at the terminals of a generator so that 150 lamps, in parallel, each requiring 0.5 ampere at 110 volts, will receive their proper current? Resistance of leads 0.02 ohm. *Ans.* 111.5 volts.

3. If the internal resistance of the generator armature in Problem 2 is 0.05 ohm, what E. M. F. is developed by the machine? *Ans.* 115.25 volts.

4. How much resistance must be inserted in series with two 50-volt 50-ohm lamps, to allow them to be placed in series across a 220-volt circuit? *Ans.* 120 ohms.

5. We desire to run a motor, requiring 1 ampere, at 6 volts from a supply circuit of 110 volts potential difference. If two 50-volt 50-ohm (hot) incandescent lamps are connected in series with the motor, how much additional resistance must be added to meet the requirements? *Ans.* 4 ohms.

6. Three coils, A, B, and C, having resistances of 6, 8, and 12 ohms respectively, are connected in parallel and then in series with a coil D of 2 ohms; if 9 amperes flows through coil B of 8 ohms, how much current flows through each of the other coils? *Ans.* 12 amperes in A, 6 amperes in C, 27 amperes in D.

7. What is the P. D. maintained across the parallel circuit in Problem 6, and what is the total pressure across the entire circuit? *Ans.* 72 volts; 126 volts.

8. The two field magnets of a bipolar generator have a resistance of 55 ohms each, and are connected in series and then connected across the brushes where 110 volts are maintained. (*a*) What is the field exciting current? (*b*) What will be the exciting current when the fields are connected in parallel and across the brushes? *Ans.* (*a*) 1 ampere; (*b*) 4 amperes.

9. You are required to construct an electric heater for a trolley car of No. 16 B. & S. iron wire which shall operate on 10 amperes. Assuming

that the potential difference between trolley wire and track is 500 volts, find the length of wire required so as to place the stove in parallel with the circuit. (Neglect the rise in resistance due to the heat.) *Ans.* 2038 feet.[1]

10. (*a*) How much resistance would you insert in circuit with a 50-volt 50-ohm incandescent lamp to place it across a 110-volt circuit? (*b*) How many feet of No. 18 B. & S. German silver wire are required to make a rheostat for this purpose? *Ans.* (*a*) 60 ohms; (*b*) 759 feet.[1]

11. Four electromagnets having resistances of 4, 6, 8, and 10 ohms respectively, are connected in series and to a battery having an internal resistance of 2 ohms. When the switch is closed a voltmeter, across the battery terminals, indicates 56 volts. (*a*) What will be the indications of a voltmeter when paralleled with each spool? (*b*) What will the voltmeter indicate when placed across the cells when the magnets are disconnected? *Ans.* (*a*) 8, 12, 16, and 20 volts; (*b*) 60 volts.

12. What will be the drop on 500 feet of No. 0 wire used as an overhead trolley line at the instant when it is supplying current to four cars, each requiring 70 amperes? *Ans.* 14 2 volts.[1]

[1] The student is advised to calculate resistances rather than take them from the wire table.

LESSON XI

ELECTRICAL WORK AND POWER

Force — Different Kinds of Force — Mass and Weight — Work — Power — Horse Power of a Steam Engine — Difference between Energy, Force, Work, and Power — Electrical Work — Electrical Power — Heat and Work — Equivalents of Mechanical and Electrical Work — Electrical Horse Power — The Kilowatt — The Watt-hour and Kilowatt-hour — Electrical Power Calculations — Power from Cells — Efficiency — Questions and Problems.

135. Force. — Force is defined as that which produces motion, or a change of motion, in matter; thus force must always be applied to any body to cause it to move. To increase, decrease, or stop this motion, that is to change it, force must again be applied. For example, to start a loaded wheelbarrow force must be applied, either by pushing or pulling it, but when it is set in motion less force will be required to keep it in motion; to cause a change in motion, that is to increase or decrease the speed, extra force must be applied. Force does not always produce motion, in some cases it only tends to produce motion; thus, when a man tries to push a laden freight car he applies all his muscular force, but no motion results.

136. Different Kinds of Force. — There is the *force of gravitation*, in virtue of which all bodies free to move will fall from a higher to a lower level. The force exerted by a man riding a bicycle or by a horse drawing a carriage are examples of *muscular force*. An engine draws a train of cars by reason of the *mechanical force* applied, which is due to the expansion of the steam in the engine cylinder. A mixture of air and illuminating gas in a room is ignited and the explosion wrecks the room; the action is due to the *chemical force* exerted. The force which produces or tends to produce a flow of electricity is *electromotive force*. The force which sets up magnetic lines of force is *magnetomotive force*. The rate at which

a train moves depends upon the force exerted by the engine, so also, the rate of flow of electricity depends upon the amount of electromotive force applied.

137. Mass and Weight. — The *mass* of a body is the quantity of matter in it; the *weight* of a body is due to the force of gravity acting upon this matter. Since the force of gravity diminishes as we ascend from the earth's surface, the attraction for a mass of matter will diminish, or it will weigh less on the top of a high mountain than at the sea level; the mass of matter, however, would be the same in each case. Weight is not, therefore, the same thing as mass, but we can conveniently measure a body by its weight.

138. Work. — Work is done when force overcomes a resistance and moves the body on which it acts, or, *work is force acting through space.* The amount of work done is measured by the product of the force and the distance through which the body moves, or

work = force × distance,

or work = pounds × feet = foot-pounds.

Work is not always done when a force acts; for instance, a man pushes with all his force against a brick wall; he is exerting force, but doing no work because no motion results, nor is any resistance overcome. If a weight be lifted, work is done directly in proportion to the weight and to the distance through which it was moved. Thus, the work done in lifting 4 pounds to a height of 3 feet is equivalent to 12 foot-pounds of work. Exactly the same work is performed when 2 pounds are raised 6 feet; or 6 pounds raised 2 feet; or 12 pounds raised one foot. Work does not always consist in raising weights; the steam engine does work by hauling a train, due to the expansive force of steam acting upon the piston; an explosion of powder in a cannon causes an iron ball to traverse a certain distance. The chemical action in a storage battery sets up a force which causes a current to flow through an electric motor, and the motor drives an automobile weighing so many pounds a certain number of miles. The work in each case is measured in foot-pounds. Whether work be done mechanically, chemically, thermally, or electri-

cally, it can be expressed in foot-pounds. The total amount of work done is independent of time, that is, the same work may be performed in one hour or one year. When different amounts of work performed in different amounts of time are to be compared, then reference is made to the time rate of working, or the *power*.

139. Power. – *Power is the rate at which work is done* and i to be distinguished from the total amount of work to be done

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

or

$$\frac{\text{foot-pounds}}{\text{time}} = \text{foot-pounds per unit of time.}$$

For example, it requires four hours for a particular engine to draw a train from one station to another, while another engine may draw the same train the same distance in two hours. One engine is thus twice as powerful as the other, because it can do the same work in one half the time. When the train had reached its destination it would have represented the same amount of work done, no matter whether it had traveled at one mile per minute or one mile per hour, leaving, of course, friction and air resistance out of account.

Power is estimated according to the amount of work done in a given period of time. As mechanical work is measured in foot-pounds, mechanical power would thus be so many foot-pounds per minute, or per second. Another mechanical unit of power is the horse power.

ONE MECHANICAL HORSE POWER = 33,000 FT. LBS. PER MINUTE, or

$$\frac{33000}{60} = 550 \text{ ft. lbs. per second.}$$

If a body weighing 33,000 pounds be raised one foot every minute then we have a rate of working equal to one horse power; or if 16,500 pounds be raised two feet per minute, the rate of working is the same, one horse power. When we say that an engine is developing 40 horse power we mean that it is performing 550 × 40 = 22,000 foot-pounds of work every second.

140. Horse Power of a Steam Engine. — The horse power of a steam engine may be readily calculated from data obtained from it while it is working. The mean pressure of the steam upon the piston is found by attaching a recording indicator to the steam cylinder which shows graphically the various steam pressures during a stroke of the piston. From this "card," as it is termed, the average or mean effective pressure throughout the stroke is obtained. The speed of the engine must be noted while the card is taken, but the length of stroke in feet and the area of the piston-head in square inches should be previously obtained.

The following formula may then be used to ascertain the rate of working, or horse power developed, corresponding to the above conditions:

$$\text{horse power of steam engine} = \frac{P \times L \times A \times N}{33000}, \quad \textbf{(50)}.$$

where P = mean effective steam pressure in pounds per sq. in. (from indicator card),
L = length of stroke in feet,
A = area of piston-head in square inches,
N = number of strokes per minute (twice the number of revolutions).

Problem 68. — The mean steam pressure of a steam engine is 45 lbs. per sq. in., the speed of the engine is 275 revolutions per minute, length of stroke is 12 inches, area of piston-head is one-half a square foot. What horse power is developed by the engine?

L = 12 inches = 1 foot, A = ½ sq. ft = 72 sq in., N = 275 rev. per min. × 2 strokes per rev. = 550 strokes per min.

By Formula (50) $\text{H. P} = \frac{P \times L \times A \times N}{33000} = \frac{45 \times 1 \times 72 \times 550}{33000} = 54 \text{ H.P.}$

141. Difference between Energy, Force, Work, and Power. It is important that the student should thoroughly understand the meaning of the above terms. *Energy* is the capacity to do work. *Force* is one of the factors of work and has to be exerted through a distance to do work, the work being reckoned as the product of the force and the distance through which it has been applied. *Work* is done when energy is expended or when force overcomes a resistance. *Power* is the rate of working

142. Electrical Work. — Work is force acting through space, or energy expended; therefore, resistance is overcome when work is performed. Force may exist without work being performed, as when you push against a table and do not move it, no work is done, yet the force exists. An electrical force exists between the two terminals of a battery, tending to send a current of electricity from one to the other through the air. The force is not sufficient to overcome the resistance of the air, therefore no current flows and the battery is not doing any work; the same is true with a generator when running on open circuit. When a wire is connected across the battery terminals, the force overcomes the resistance of the wire and electricity is moved along, around or through the wire. The electrical work, or energy expended, is represented by the amount of heat generated in this instance, ¶ 237. With a small lamp connected to the battery, the work is represented by the heat and light given by the lamp as well as the heat given off by the remainder of the circuit. The total work performed is the product of the force, the current, and th time that the current is maintained, or

$$\text{electrical work} = \text{volts} \times \text{amperes} \times \text{seconds}.$$

The unit of electrical work is the amount of work performed by a current of one ampere flowing for one second under a pressure of one volt and is called a joule.

Since an ampere flowing for one second is equal to one coulomb, ¶ 93, a joule is, therefore, one volt-coulomb and is analogous to the mechanical unit of work, the foot-pound. The joule is not as large as the foot-pound; it develops that

$$1 \text{ joule} = 0.7375 \text{ foot-pound},$$
$$1 \text{ foot-pound} = 1.356 \text{ joules}.$$

Larger units of electrical work are given in ¶ 148.

TO FIND THE TOTAL ELECTRICAL WORK, IN JOULES, PERFORMED IN ANY CIRCUIT:

Multiply the volts causing the current to flow by the current in amperes and the time in seconds.

$$\text{Joules} = \text{volts} \times \text{amperes} \times \text{seconds},$$

or

$$W = E \times I \times t \quad \text{.................... (51).}$$

Problem 69. — A current of 20 amperes is maintained through a number of incandescent lamps for one hour by a pressure of 110 volts. How much electrical work has been performed?

Here the time is $60 \times 60 = 3600$ seconds.

By Formula (51) $W = E \times I \times t = 110 \times 20 \times 3600 = 7{,}920{,}000$ joules.

To find the total electrical work, in joules, performed in any part of the circuit when the current and resistance are known:

Multiply the square of the current by the resistance, and this product by the time the current flows.

$$W = I \times R \times I \times t,$$

or

$$W = I^2 \times R \times t. \quad \ldots \ldots \ldots \ldots \quad (52)$$

By substituting for E in Formula (51) its value I × R, we get Formula (52). Also by substituting the value of I, which equals E ÷ R, in Formula (51), we obtain an expression to find the work in joules when the voltage and resistance are known, as follows:

By Formula (51) $W = E \times I \times t = E \times \frac{E}{R} \times t,$

or

$$W = \frac{E^2}{R} \times t. \quad \ldots \ldots \ldots \ldots \quad (53).$$

Problem 70. — A current of 5 amperes is passed for one-half hour through an arc lamp, the resistance of which is 4 ohms. How much energy has been expended?

By Formula (52) $W = I^2 \times R \times t = 5 \times 5 \times 4 \times 1800 = 180{,}000$ joules.

Problem 71. — The resistance of the copper cables connecting a generator with its switchboard is 0.1 ohm, and 2 volts are required to send the full-load current through them. How much energy is expended in 10 hours?

By Formula (53) $W = \frac{E^2}{R} \times t = \frac{2 \times 2}{0.1} \times 36{,}000 = 1{,}440{,}000$ joules.

143. Electrical Power. — Power is the rate at which energy is expended, and is independent of the total work to be accomplished. The rate of working, or the power, is found by dividing the total work by the time required to perform it.

$$\text{Electrical power} = \frac{\text{electrical work}}{\text{time}}.$$

The unit of electrical power is a unit of work performed in a unit of time; one unit is the joule per second, and is called a *watt.* Therefore,

$$\text{watts} = \frac{\text{joules}}{\text{seconds}} = \frac{\text{volts} \times \text{amperes} \times \text{seconds}}{\text{seconds}} = \text{volts} \times \text{amperes}.$$

One watt, therefore, equals one volt multiplied by one ampere.

1. To find the rate in watts at which energy is expended in a circuit.

Multiply the current in amperes by the pressure causing it to flow.

Let P = watts expended,
I = current in amperes,
E = pressure in volts.

Then since watts = volts × amperes,

$$P = E \times I \quad \ldots \ldots \quad (54).$$

2. To find the current when the power and pressure are known:

Divide the watts expended by the voltage causing the current to flow.

From Formula (54), amperes $= \frac{\text{watts}}{\text{volts}}$,

or

$$I = \frac{P}{E} \quad \ldots \ldots \quad (55).$$

3. To find the pressure when the power and current are known:

Divide the watts expended by the current flowing.

From Formula (54), volts $= \frac{\text{watts}}{\text{amperes}}$,

or

$$E = \frac{P}{I} \quad \ldots \ldots \quad (56).$$

Problem 72. — How many watts are consumed by one hundred incandescent lamps connected in multiple to a 110-volt circuit, supposing each lamp to have a resistance (hot) of 220 ohms?

$$I = \frac{E}{R} = \frac{110}{220} = \frac{1}{2} \text{ ampere per lamp.}$$

$P = E \times I = 110 \times \frac{1}{2} = 55$ watts per lamp. $55 \times 100 = 5500$ watts.

Problem 73. — What current is taken by a 20-watt lamp on a 100-volt circuit?

By Formula (55) $I = \frac{P}{E} = \frac{20}{100} = 0.2$ **ampere.**

Problem 74. — A 500-watt motor requires a current of 10 amperes. What E. M. F. is necessary to operate it?

By Formula (56) $E = \frac{P}{I} = \frac{500}{10} = 50$ volts.

144. Heat and Work. — One of the most important discoveries in science is that of the *equivalence of heat and work*, that is, that a *definite quantity of mechanical work can always produce a definite quantity of heat, and, conversely, this heat, if the conversion be complete, can perform the original quantity of work.*

All kinds of energy (chemical, mechanical, electrical, etc.) are so related to each other that energy of any kind can be changed into energy of any other kind. This statement is known as the doctrine of *correlation of energy.* When one form of energy disappears an exact equivalent of another form takes its place, so that the sum total of the energy is not changed. This is known as the doctrine of *conservation of energy.* These two principles constitute the corner-stone of physical science.

145. Equivalents of Mechanical and Electrical Work. — Dr. Joule, of England, was the first to ascertain the relation existing between mechanical work, heat, and electricity. In an experiment he caused a paddle-wheel to revolve in a vessel filled with water, by means of a falling weight attached to a cord and wound around the axle of the wheel (Fig. 109). The resistance offered by the water to the motion of the paddles was the means by which the mechanical motion of the weight was converted into heat, which resistance raised the temperature of the water. From this experiment it was found that 778 foot-pounds of work would raise the temperature of 1 pound of water 1° Fahrenheit; also by the doctrine (¶ 144), the heat which would raise 1 pound of water 1° Fahrenheit would also raise 778 pounds 1 foot. The quantity, 778 foot-pounds, is called the *mechanical equivalent of heat,* or Joule's

equivalent. If now we heat the pound of water by a current of electricity until its temperature is raised 1°, we will have done the same work electrically as was previously done mechanically. An apparatus similar to the calorimeter (¶ 238) would be suitable for this experiment. The current in amperes and the pressure in volts must be accurately read from instruments. From this experiment it was found that a current of 1 ampere flowing through the coil under a pressure of 1 volt (or 1 watt expended) would do the same work as 0.7375 foot-pound expended in 1 second. The rates of working are thus equal, since the same work in each case has been accomplished in the same time.

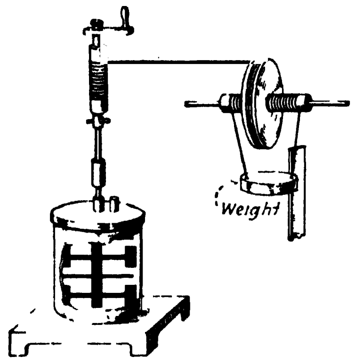


Fig 109.- Joule's Paddle-wheel Experiment.

Therefore,

$$1 \text{ watt} = 0.7375 \text{ foot-pound per second},$$

or

$$1 \text{ foot-pound per second} = 1.356 \text{ watts}.$$

Now, since 550 foot-pounds per second are equivalent to 1 mechanical horse power (¶ 139), an equivalent rate of electrical working would, therefore, be:

$$\frac{550}{0.7375} = 746 \text{ watts} = 1 \text{ electrical horse power}.$$

A current of 1 ampere at 746 volts, or 746 amperes at 1 volt, etc., maintained through the calorimeter coil for 1 second would heat the water to exactly the same temperature that it would be heated by the paddle wheels when, in 1 second, 550 pounds fall through a distance of 1 foot, or 1 pound falls through 550 feet, etc. If these rates of working are continued for equal periods of time, as an hour, or a day, the water is raised to the same temperature by either method, so that the total work performed is also the same.

146. Electrical Horse Power. — In ¶ 145 the method of obtaining the equivalent of a mechanical horse power in electrical units was given. The watt being a very small unit of power, the larger unit, *electrical horse power*, is often used.

TO FIND THE ELECTRICAL HORSE POWER (H.P.) MAINTAINED IN ANY CIRCUIT, OR PART OF A CIRCUIT:

Multiply the volts causing the current to flow by the current expressed in amperes and divide this product by 746.

$$\text{H. P.} = \frac{\text{watts}}{746} = \frac{\text{volts} \times \text{amperes}}{746} = \frac{E \times I}{746} \quad . . . \quad \textbf{(57)}.$$

Problem 75. — A generator maintains a pressure of 110 volts across an electric-light circuit, and the ammeter indicates 100 amperes; what horse power is being developed by the machine?

By Formula (57) $\quad \text{H. P.} = \frac{E \times I}{746} = \frac{110 \times 100}{746} = 14.7 \text{ H. P.}$

147. The Kilowatt. — The *kilowatt* (abbreviated kw.) is a larger unit of electrical power. *One kilowatt equals* 1000 *watts*, or is about $1\frac{1}{3}$ times as large as the horse power unit.

$$\text{Kilowatts (kw.)} = \frac{\text{watts}}{1000} = \frac{E \times I}{1000} \quad . . . . \quad \textbf{(58)}.$$

$$\text{Watts} = \text{kw.} \times 1000 \quad . . . . \quad \textbf{(59)}.$$

$$1 \text{ H. P.} = 0.746 \text{ kw.}$$
$$1 \text{ kw.} = 1.34 \text{ H. P.}$$

Problem 76. — What is the capacity in kilowatts of a generator carrying a load of 500 amperes at 120 volts?

By Formula (58) $\quad \text{kw.} = \frac{E \times I}{1000} = \frac{120 \times 500}{1000} = 60 \text{ kw.}$

Problem 77. — How many amperes will be maintained by a 40-kw. generator at a pressure of 100 volts?

By Formula (59) Watts = kw × 1000 = 40 × 1000 = 40,000 watts.

By Formula (55) $\quad I = \frac{P}{E} = \frac{40000}{100} = 400$ amperes.

148. The Watt-hour and Kilowatt-hour. — The joule is a very small unit of electrical energy or work, so that larger units are generally used in practice. A *watt-hour* is one watt

exerted or expended for one hour. It is equivalent to 3600 watt-seconds (or joules) or also to 60 watt-minutes.

Watt-hours = watt × hours.

The dials of consumer's meters, used to measure the electrical energy supplied for lighting and power, generally record watt-hours, ¶ 226. A *kilowatt-hour* is a larger unit of electrical work and is equal to 1000 watts or 1 kw. maintained for one hour, or 500 watts maintained for two hours, etc.

Kilowatt-hours = kw. × hours.

An electrical *horse-power-hour* is one electrical horse power maintained for one hour, or 746 watts maintained for one hour.

Horse-power-hours = H. P. × hours.

Electrical energy is generally supplied from stations at a fixed rate per horse-power-hour or kilowatt-hour. The total cost of producing a kilowatt-hour varies with many station conditions; from about 1 to 7 cents per kilowatt-hour is the range in a number of plants.

149. Electrical Power Calculations. — The following rules and formulæ have been derived either by transposing the formulæ in ¶¶ 143 to 148, or by combining them with the formulæ given in Lesson VIII, Ohm's Law. This lesson is very important in the solution of many practical problems. The formulæ apply equally well to the whole, or any part of a circuit; as, for example, to the lead wires to a lamp as well as to the lamp itself, or the internal resistance of a battery or dynamo. *Caution must be exercised to use the volts lost or drop,* ¶ 131, *in the particular part of any circuit considered, also the resistance of, and the current through, this part only.* The symbols used to represent the quantities are as given heretofore.

Case 1. — GIVEN CURRENT AND PRESSURE, TO FIND THE WATTS EXPENDED:

The watts lost or expended in any circuit equals the product of the current and the pressure causing it to flow, **Formula (54).**

$$P = E \times I.$$

Case 2. — GIVEN CURRENT AND RESISTANCE, TO FIND THE ENERGY EXPENDED IN WATTS:

The watts lost or expended in any circuit are equal to the current squared multiplied by the resistance. This is often called the "I-square R loss".

$$P = I^2 \times R. \quad \ldots\ldots\ldots \quad \textbf{(60)}.$$

This formula is obtained by substituting the value of $E = I \times R$ in Formula (54).

Problem 78. — The resistance of the field magnets of a dynamo is 220 ohms and the magnetizing current is 2 amperes. What energy is expended?

By Formula (60) $P = I^2R = 2 \times 2 \times 220 = 880$ watts

Case 3. — GIVEN RESISTANCE AND PRESSURE, TO FIND THE WATTS EXPENDED:

The watts lost or expended in any circuit are equal to the square of the pressure divided by the resistance.

$$P = \frac{E^2}{R} \quad \ldots\ldots\ldots \quad \textbf{(61)}.$$

This formula is obtained by substituting the value of $I = \frac{E}{R}$ in Formula (54).

Problem 79. — The resistance of a telephone relay is 200 ohms. What power is expended in the relay when operated on 24 volts? What current does it take?

By Formula (61) $P = \frac{E^2}{R} = \frac{24 \times 24}{200} = 2.88$ watts.

By Formula (27) $I = \frac{E}{R} = \frac{24}{200} = 0.12$ ampere.

Case 4. — GIVEN WATTS EXPENDED AND CURRENT, TO FIND THE RESISTANCE:

The resistance is equal to watts expended divided by the square of the current.

$$R = \frac{P}{I^2} \quad \ldots\ldots\ldots \quad \textbf{(62)}.$$

This formula is found by transposing Formula (60).

Problem 80. — A 55-watt incandescent lamp requires 0.5 ampere. What is its resistance?

By Formula (62) $R = \frac{P}{I^2} = \frac{55}{0.5 \times 0.5} = \frac{55}{0.25} = 220$ ohms

Case 5. — GIVEN WATTS EXPENDED AND RESISTANCE, TO FIND THE CURRENT:

The current equals the square root of the watts divided by the resistance.

$$I = \sqrt{\frac{P}{R}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (63).$$

This formula is obtained by transposing Formula (60).

Problem 81. If the hot resistance of a 55-watt lamp is 220 ohms, what current will it require?

By Formula (63) $I = \sqrt{\frac{P}{R}} = \sqrt{\frac{55}{220}} = \sqrt{\frac{1}{4}} = \frac{1}{2}$ ampere.

Case 6. — GIVEN WATTS EXPENDED AND PRESSURE, TO FIND THE RESISTANCE:

The resistance equals the square of the pressure divided by the watts expended.

$$R = \frac{E^2}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (64).$$

This formula is obtained by transposing Formula (61).

Problem 82. — What is the resistance of a 55-watt, 110-volt incandescent lamp?

By Formula (64) $R = \frac{E^2}{P} = \frac{110 \times 110}{55} = 220$ ohms.

In the above formulae if the value of P is given in the larger unit of power, the horse power, or if it is desired to express its value in the larger unit, the formulae may be changed by remembering that 1 horse power = 746 watts.

150. Power from Cells. — The amount of power that can be furnished by a cell is directly proportional to the square of its E. M. F. divided by its internal resistance and is equal to the number of watts expended by the cell on short-circuit. Let P represent the power in watts from a single cell, then from Formula (61) we get

$$P = \frac{E^2}{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (65).$$

The power obtained from any number of similar cells is equal to the power of one cell multiplied by that number, and is independent of the grouping, provided that it is symmetrical. For example, the amount of power a dry cell can furnish, if the E. M. F. is 1.5 volts and internal resistance is 0.25 ohm, is $P = \frac{E^2}{r} = \frac{1.5 \times 1.5}{0.25} = 9$ watts. The power furnished by ten cells would be $10 \times 9 = 90$ watts.

If arranged all in series then the total E. M. F. = 15 volts and total internal resistance = 2.5 ohms, and

$$P = \frac{E^2}{r} = \frac{15 \times 15}{2.5} = 90 \text{ watts.}$$

If arranged all in parallel, then the total E. M. F. = 1.5 volts and the internal resistance = 0.025, and

$$P = \frac{E^2}{r} = \frac{1.5 \times 1.5}{0.025} = 90 \text{ watts, as before.}$$

In the above cases all the energy is expended inside the cell, no external resistance being considered.

151. Efficiency. — By efficiency is meant the relation of the useful work done to the total energy expended. The efficiency of a device is the ratio of energy delivered by it to the energy supplied to it. A perfect battery or generator (that is, one with no internal resistance) would deliver all of the energy to the external circuit, but as some portion of it is lost in the internal resistance the useful energy is always less than the total energy expended. *The efficiency of a battery is the ratio of the external energy to the total energy developed, and this is the same as the ratio of the external to the total resistance in the circuit.* If the total energy expended is represented by 100, and one half of this amount is unavailable for useful work, the efficiency would be 50 per cent.

To find the efficiency of a battery:

Divide the resistance of the external circuit by the resistance of the external circuit plus the resistance of the battery.

$$\text{Efficiency} = \frac{R}{R + r} \quad \ldots\ldots\ldots\ldots \quad (66).$$

Problem 83. — What is the efficiency of a battery delivering current through an external resistance of 3 ohms when the battery resistance is 3 ohms?

By Formula (66) efficiency $= \frac{R}{R + r} = \frac{3}{3 + 3} = 0.50$ or 50%

Suppose the current furnished by the battery is 2 amperes, then the power expended in the external resistance will be $I^2 \times R = 2^2 \times 3 = 12$ watts; the internal resistance being of the same value as the external, the same amount of power is there expended, so that the efficiency is the ratio of

$$\frac{\text{useful watts}}{\text{total watts expended}} = \frac{12}{24} = 0.50 = 50\%, \text{ as before.}$$

Let P = useful energy expended in watts,
p = useless energy expended in watts.

Then,

$$\text{efficiency} = \frac{P}{P + p} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(67)}.$$

QUESTIONS

1. What is the difference between force and work?
2. Define mass, energy, power, weight.
3. What is the unit (*a*) of mechanical power? (*b*) of mechanical work? (*c*) of electrical work? (*d*) of electrical power?
4. Cite examples illustrating the conservation and correlation of energy.
5. How would you ascertain, by experiments, the mechanical equivalent of work performed by an electric current?
6. What is the difference between a kilowatt and a kilowatt-hour?
7. A battery used in electroplating has an efficiency of 70 per cent What do you understand by this statement?

PROBLEMS

1. How much electrical power is expended in illuminating a 16-candle power incandescent lamp, supposing that it has a resistance of 220 ohms (hot) and is taking 0.5 ampere? How many watts per candle power? How many such lamps can be maintained at full candle power by one mechanical horse power? *Ans.* 55 watts; 3.43 watts; 13 lamps.
2. A number of 110-volt incandescent lamps are being lighted by a generator having a P. D. of 112 volts at the brushes. The resistance of the leads carrying current to the lamps is 0.05 ohm. Each lamp requires 50 watts. How many lamps are burning? *Ans.* 88 lamps.

3. (*a*) What size of generator (kilowatt capacity) should be purchased for a 500-lamp installation, supposing that 50-watt incandescent lamps are to be adopted? (*b*) What would be the kw. capacity of a motor required to be substituted for a 25-horse-power gas engine? *Ans.* (*a*) 25 kw.; (*b*) 18.65 kw.

4. In constructing a solenoid and core to actuate a lever, 500 feet of number 18 B. & S. copper magnet wire is wound upon a brass spool. A table of heating limits gives 4 amperes as a safe carrying capacity for this size of wire under these conditions. Using this current, how much extra resistance must be added to place the coil across a line of 110 volts potential difference? *Ans.* 24.24 ohms.

5. The above solenoid is to operate in series with the field magnets of a dynamo having 20 ohms resistance. (*a*) How much extra resistance must now be added to place the fields and coil in series across the above mains so as to receive the same current? (*b*) How many feet of No. 18 B. & S. iron wire are required to construct a rheostat for the extra resistance in this problem? (*c*) How much energy is consumed in the solenoid? *Ans.* (*a*) 4.24 ohms; (*b*) 110 feet; (*c*) 52.1 watts.

6. A street car is driven by two four-pole series motors. Each field magnet has a resistance of 0.125 ohm, the armature has 0.125 ohm and an extra rheostat has 4 ohms. The E. M. F. between trolley wire and rails is 500 volts. Neglecting the counter E. M. F. of the motors, find the current the motors will receive in the following positions of the controller switch — (*a*) first point: both motors in series, all field coils in series, extra resistance in series. (*b*) fourth point: both motors in parallel and the extra resistance in series with them. (*c*) What power is the car receiving on the fourth point? (*d*) Make a sketch of both controller combinations. *Ans.* (*a*) 95.2 amperes; (*b*) 115.9 amperes; (*c*) 77.7 H. P.

7. An electric automobile is equipped with 40 storage cells which are connected, through the controller switch, for the first speed, 20 cells in series and two groups in parallel. Each cell has an E. M. F. of 2 volts and an internal resistance of 0.1 ohm. The resistance of the motors, extra resistance and leads at this combination is 0.5 ohm. (*a*) What is the value of the current required to start the vehicle? (*b*) How much power is expended at the start? *Ans.* (*a*) 26.6 amperes; (*b*) 1061 watts.

8. While visiting an electric light station you note the following indications of instruments on the switchboard: voltmeter 115, ammeter 330. The plant operates the two-wire direct-current system. What is the load on the generator expressed in kilowatts and electrical horse power? *Ans.* 37.95 kw.; 50.87 H. P.

9. A compound-wound generator is connected to a circuit to which the following apparatus is wired: 150 incandescent lamps, each requiring 0.6 ampere; 3 arc lamps taking 10 amperes each; various electrical cooking and heating appliances requiring when all are at work 20.5 amperes; two electroplating and electrotyping baths arranged in series across the mains and taking a maximum current of 5 amperes; 10 storage cells in series with a lamp-bank resistance across the mains and requiring a charging current of 10 amperes. The two-wire direct-current system

is used and a constant potential difference of 110 volts is maintained between the mains. What is the output of the generator in electrical horse power, supposing that the maximum current ever required is 75 per cent of that taken when the whole installation is in operation? *Ans.* 17.19 H. P.

10. The mean effective steam pressure from an indicator card is 50 pounds per sq. in.; the speed of the engine is 290 revolutions per minute; the length of stroke is 10 inches; the area of piston head is 0.75 square foot. What horse power is developed by the engine? *Ans.* 78.77 H. P.

11. What is the current flowing through an electromagnet having a resistance of 50 ohms and requiring 200 watts? *Ans.* 2 amperes.

12. What is the maximum power obtainable from a Grenet cell of 2 volts E. M. F. which has an internal resistance of 0.02 ohm? *Ans.* 200 watts.

13. (*a*) What is the efficiency of a battery of 31 cells in series delivering current to four 50-volt, 50-watt incandescent lamps (resistance assumed constant) in parallel? Each cell has an E. M. F. of 2 volts and an internal resistance of 0.1 ohm. (*b*) What power is expended in the battery? *Ans.* (*a*) 78%; (*b*) 51.1 watts.

LESSON XII

STORAGE BATTERIES

The Storage or Secondary Cell — Direction of Current in a Storage Battery on Charge and Discharge — Chemical Action in a Lead Storage Cell — The Electrolyte in a Lead Cell — The Hydrometer — The Voltage of a Lead Storage Cell — Types of Lead Plates used in Storage Cells — The Rated Capacity of a Storage Cell or Battery — Care and Maintenance of Lead Cells — The Nickel-Alkali or Edison Storage Cell — Efficiency of a Storage Cell — Methods of Charging — Uses of Storage Batteries — Questions.

152. The Storage or Secondary Cell. — A storage cell is a voltaic cell consisting of two plates of metals or metallic compounds immersed in an electrolyte, the materials of the plates and electrolyte being so chosen that the cell, after having delivered an electric current for a certain time, may be restored to its original condition in a simple and efficient manner. This restoration is accomplished by sending a current from an outside source of electricity through the cell in a direction opposite to that of the current supplied by the cell; this process is called *charging*. When the cell delivers current to an external circuit it is said to be *discharging*.

The difference between a primary cell and a secondary cell is as follows: The *primary cell* consists of two dissimilar plates and an electrolyte that will act chemically on the positive plate (zinc) when the external circuit is closed, thereby converting the chemical energy of the cell into an electric current. When the zinc is almost consumed, it is replaced with a new one and fresh electrolyte is added in order to restore the cell to its initial condition. In a *secondary cell* the plates and electrolyte are of such materials that there is no chemical action between them until after a current has first been sent through the cell; that is, the cell must first have been charged. As the materials become exhausted in discharging the cell, they are capable of being renewed by the passage of an electric

current through the cell in a direction opposite to that of the current on discharge. Charging a storage cell means that the electrical energy supplied to it is converted into chemical energy which is stored in the cell, and discharging means that this chemical energy is transformed back again to electrical energy in maintaining a current through an external circuit. When two or more storage cells are electrically connected (usually in series) they form a *storage battery*, or *secondary battery*, or *accumulator*.

Experiment 55. Place two copper strips in a solution of zinc sulphate contained in a small battery jar. Connect the terminals of the copper strips to a galvanometer, and note that the needle is *not* deflected, because the combination does not conform to the definition of a voltaic cell, ¶ 29. Disconnect, and substitute for the galvanometer two bichromate cells connected in series. By electrolysis, part of the zinc sulphate ($ZnSO_4$) is converted into sulphuric acid (H_2SO_4), and metallic zinc is deposited on one of the copper plates. After the action has taken place for a little while, disconnect the battery and again connect the electrolytic cell to the galvanometer, and note that its needle *is* now deflected.

No electricity was stored in Experiment 55, but a chemical action took place, which changed the plates into two dissimilar metals and the salt (zinc sulphate) into an acid capable of attacking one of them, thus conforming to the definition of a primary cell. The chemical action on discharge of this simple type of accumulator will be obviously the same as in the voltaic cell of ¶ 36, since the plates (copper and zinc) and the acid (sulphuric) are identical with those of that cell. On discharge the zinc is consumed by the acid, and when it is all dissolved in the solution the cell is entirely discharged and must be recharged again by electrolysis.

Experiment 56. - Place two lead strips in the U-tube (Fig. 70), fill with acidulated water, and connect the plates to a detector galvanometer. No deflection is noted. Now connect the plates to two bichromate cells (in series), and after passing a current for a short time examine the plates, and you will find that the positive plate has become brownish in color, while the negative plate is lighter in color. Connect the plates to the galvanometer, and note that the needle indicates the discharging current.

Lead plates in dilute sulphuric acid were first used by Planté, from whom this type of cell takes its name. The charging action just described changes the positive lead (Pb) plate to

lead peroxide (PbO_2), while the negative plate is left in the form of spongy lead. On discharging the cell both the peroxide plate and the lead plate are gradually reduced to lead sulphate ($PbSO_4$), which forms a whitish coating on the plates. The positive and negative plates are readily distinguished by their color — the positive is a dark brown and the negative a light gray.

153 Direction of Current in a Storage Battery on Charge and Discharge. — Upon charging the cell in Experiment 55, the direction of current inside the cell was from copper to zinc; upon discharge, the current inside the cell travels in the opposite direction (zinc to copper, as in a voltaic cell). In Experiment 56, the direction of the charging current inside the cell was from the positive (lead plate) to the negative (lead plate); upon discharge the current was from the terminal of the positive (lead peroxide) plate through the galvanometer to the negative-plate terminal, and from the negative plate to the positive plate *inside* the cell. Consequently the positive terminal of a storage battery must be connected to the *positive* terminal of the charging lines, in order that this same terminal will again be positive on discharge.

There are two kinds of storage batteries in use, namely: the lead-acid battery, and the nickel-alkali or Edison battery. The lead cell will be considered first.

154. Chemical Action in a Lead Storage Cell. — Referring again to Experiment 56, it will be recalled that when the cell was in a charged condition the positive plate was lead peroxide (PbO_2), and the negative plate was spongy lead (Pb). These plates are the *active materials* of commercial lead-acid storage batteries, and the electrolyte is a solution of sulphuric acid (H_2SO_4) and water (H_2O). When such a storage cell is discharging, the current which is in the direction from the negative plate to the positive plate inside the cell breaks up the electrolyte into hydrogen (H_2), which goes to the positive plate, and the radical SO_4, which travels to the negative or sponge, lead plate. At the latter electrode, the radical SO_4, unites directly with the sponge lead to form lead sulphate ($PbSO_4$). The hydrogen which is liberated at the positive or lead peroxide plate, together with some hydrogen derived from sulphuric

acid in contact with that plate, unites with the oxygen of the lead peroxide and forms water. The SO_4 of the latter acid unites with the lead of the lead peroxide plate and changes it to lead sulphate ($PbSO_4$). Thus both plates are gradually converted into lead sulphate. If both plates were reduced entirely to lead sulphate the cell would no longer deliver current, for there would then be but one kind of material present, and a battery must have two dissimilar materials. In practice, the discharge of a lead cell is not continued until both plates are completely reduced to lead sulphate, because lead sulphate has (1) a very high electrical resistance, and (2) is more bulky than the active material. Because of its greater bulk, the sulphate clogs up the space occupied by the active material in the plates and if excessive tends to "buckle" or warp them.

Assuming, however, that both plates have been completely reduced to lead sulphate by a full discharge of the cell, and a current from an outside source is then sent through for charging it, the chemical action is as follows: The charging current breaks up the water, which was formed during the discharge, into hydrogen and oxygen gas. The hydrogen is liberated at the negative plate, where it unites with the SO_4 of the lead sulphate ($PbSO_4$) to form sulphuric acid (H_2SO_4), and leaving pure spongy lead. The oxygen liberated at the positive plate, together with some oxygen from water in solution, unites with the lead of the lead sulphate, and forms lead peroxide (PbO_2). The SO_4 radical of the positive plate enters into chemical union with the hydrogen liberated from the water and forms sulphuric acid (H_2SO_4). When the positive and negative plates have been completely converted respectively into lead peroxide and pure lead, the battery is back in its condition prior to discharge, and is again ready to supply current. The foregoing chemical actions on discharge and charge of a lead cell may be represented by the following equations in which the electrolytes are indicated by braces:

DISCHARGE

$$\begin{array}{llll} \text{Positive} & PbO_2 + & \left(\begin{array}{l} H_2 \\ SO_4 \end{array}\right) + H_2SO_4 & = PbSO_4 + 2\,H_2O \\ \text{Negative} & Pb \;\;\; + & & = PbSO_4 \end{array}$$

CHARGE

$$\begin{array}{ll}\text{Positive } PbSO_4 + \left(\begin{array}{l}SO_4\\ H_2\end{array}\right) + 2H_2O = PbO_2 + 2H_2SO_4 \\ \text{Negative } PbSO_4 + \qquad\qquad\qquad\quad = Pb + H_2SO_4.\end{array}$$

These four equations may be collected into a single expression as below

$$\text{Both plates} \quad PbO_2 + Pb + 2\,H_2SO_4 \rightleftarrows 2\,PbSO_4 + 2\,H_2O.$$

Reading the last equation from left to right the reactions are those which take place on discharge, while reading from right to left the reactions are those accompanying charge of a lead storage cell.

155. The Electrolyte in a Lead Cell. — The liquid in a lead storage cell is a solution of sulphuric acid and water, the percentage of acid varying from 22 to 37% by volume depending on the type of cell. It is important to have the electrolyte of the right strength or the cell will not function properly. The concentration of the electrolyte, or the proportion of acid to water, can best be determined from measurements of its *specific gravity*. The specific gravity of a liquid is a measure of its density or weight per unit of volume as compared with that of chemically pure water. If the density of water be taken as unity (or 1), it is found that solutions of acid, etc., are heavier than water or have a density exceeding unity. Thus the specific gravity of the electrolyte of one type of lead storage cell is approximately 1.2, which means that if a cubic centimeter of water weighs one gram, one cubic centimeter of the electrolyte will weigh 1.2 grams. The greater the proportion of acid in the electrolyte of a storage cell, the higher will be the reading of its specific gravity. The specific gravity of pure sulphuric acid is 1.835 (at 60° F.). It is quite common in dealing with storage batteries to call the specific gravity of water 1000 rather than unity; then the foregoing electrolyte would have a specific gravity of 1200.

The electrolyte should be made of either distilled or rain water mixed with chemically pure concentrated sulphuric acid. The proportion of water differs with several types of cell from 2.5 to 5 parts of water by volume to 1 part of acid, as specified in the directions supplied by the manufacturer with the cells.

The proper specific gravity for a cell depends somewhat upon the use for which it is intended. A cell under continuous operation may have a higher density than one which frequently stands unused for long intervals of time. In the latter case, the use of strong acid would change the active material into lead sulphate when standing idle more rapidly than if weaker acid were used. It is, however, of advantage to employ as high a density as practicable, for then the cell will have a low internal resistance and yield a high E. M. F. To make electrolytes of the proper specific gravity for use in lead storage batteries, the following proportions *by volume* of pure water to one part of acid are used:

Density	*Sulphuric Acid*	*Water*
1200	1 part	4.3 parts
1250	1 part	3.2 parts
1275	1 part	2.8 parts
1300	1 part	2.5 parts

Acid *must always be poured into the water*, preferably in a glass, china, or earthenware vessel, and must be allowed to cool before specific gravity readings are made.

The acid of a lead storage cell becomes weaker during discharge of the cell, and stronger as the cell is recharged. This fact is displayed by the equations of ¶ 154, since sulphuric acid is replaced by water during discharge, and vice versa. The condition of a cell, with regard to charge or discharge, is then readily ascertained by testing the specific gravity of its electrolyte, which test is conveniently made with a hydrometer, ¶ 156. When fully charged the electrolyte should have a specific gravity of from 1200 to 1280, according to the class of work for which the cell is intended. On discharge the specific gravity should never fall below 1175.

156. The Hydrometer. — The density or specific gravity of the electrolyte in a storage cell is measured by an instrument known as a *hydrometer*. One type is illustrated in Fig. 110, and consists of a long glass tube, near the bottom of which are two bulbs. The lower and smaller bulb is loaded with mercury or shot so as to cause the instrument to float in a vertical position when placed in the liquid. The upper bulb is filled with air and its volume is such that the whole instrument

is lighter than an equal volume of water. There is a graduated scale placed inside the upper part of the glass tube. When dropped into a solution of acid, the hydrometer sinks to a certain depth, depending upon the density of the liquid. The reading of the hydrometer scale at the surface of the solution is a measure of its specific gravity.

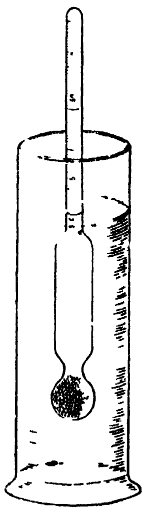


Fig. 110.—Acid Hydrometer.

In the large storage batteries used in central stations there is sufficient room in the cells to float the hydrometer in their electrolytes. But in using this instrument (Fig. 110) to test the electrolyte in a portable storage cell, enough liquid would have to be transferred to a separate glass jar to float the hydrometer. A more convenient instrument for this purpose, and one that is extensively used for testing the condition of storage batteries used on automobiles, is shown in Fig. 111. It consists of a small hydrometer within a glass-barrel syringe, which has a rubber bulb at its upper end for drawing enough liquid into the glass barrel to float the hydrometer.

157. The Voltage of a Lead Storage Cell.—The voltage of a storage cell does not depend upon the size of the cell, but does depend upon the character of the electrodes, the specific gravity of the electrolyte, and the condition of charge. The

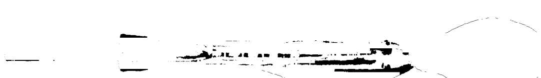


Fig. 111.—Hydrometer Syringe.

voltage of a lead storage cell is roughly 2 volts. While being charged, its voltage is from 2.0 to 2.6 volts, increasing as the charge progresses. As the battery discharges, the voltage gradually decreases, from about 2.1 to 1.7 volts.

The fall in voltage on discharge is due to the weakening of the electrolyte and to the changing of the pure active materials into a mixture of active material and lead sulphate; the formation of the latter increases the internal resistance of the cell,

and the surface layer of lead sulphate prevents access of the electrolyte to the interior pores of the active material. It is good practice not to discharge the cell below 1.8 volts, and if the discharge is carried to that point a charging current should be sent through the cell within a reasonable time, for if a cell is discharged to that voltage and the plates are left to stand in the acid, further sulphating will take place rapidly. The limiting voltage beyond which discharge should not be carried depends upon the rapidity of discharge. The value of 1.8 volts above given applies to the so-called "normal" discharge rate, ¶ 159; if the discharge of an emergency battery takes place in one hour the voltage may safely be allowed to fall to 1.6 volts.

158. Types of Lead Plates Used in Storage Cells. — In all lead-acid storage cells, as stated in ¶ 154, the *active materials* are lead peroxide at the positive plate and sponge lead at the negative plate. These active materials have no mechanical strength, and therefore in order to make them into suitable plates it is necessary that they be supported in frames or grids. These grids are usually of lead-antimony alloy, which is an alloy not attacked by the sulphuric acid electrolyte; therefore no local action occurs. In the production of battery plates there are two general types, the *Planté* or *formed type* and the *Faure* or *pasted type*.

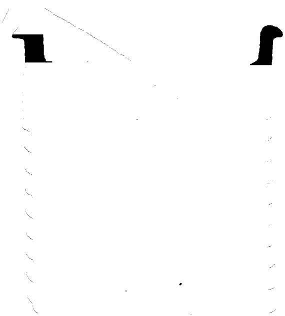


Fig. 112. — "Manchester" Positive Plate.

In the Planté type of plate the active materials are formed on the surfaces of the plates by chemical or electro-chemical means from the lead plates themselves. Since the layer of active material produced in this way is relatively thin, the production of a sufficiently large quantity to render each plate of suitable capacity demands that the area exposed to the electrolyte be as large as possible. This increased surface is procured by making grooves or ribs in the plate, or by making up the plate of long narrow ribbons of lead which are folded

in various ways to form a plate of thickness equal to the width of the ribbon. The *Manchester* form of Planté plate (Fig. 112), manufactured by the Electric Storage Battery Company, consists of a grid cast of lead-antimony in which are a number of circular holes $\frac{3}{4}$ inch in diameter. Soft corrugated pure lead ribbon is rolled into spiral buttons or "rosettes" and forced into the holes of the grid by hydraulic pressure, which securely locks them in position. During the forming process the buttons expand, thus improving the electrical contact. The *Tudor* form of Planté plate (Fig. 113), also manufactured by the Electric Storage Battery Co., is a cast plate, consisting of a single piece of lead with a number of vertical ribs extending from face to face, allowing thorough circulation of the electrolyte through the narrow spaces. At suitable intervals these ribs are supported by horizontal ribs to insure proper rigidity. The *Gould* plate, made by the Gould Storage Battery Company, is "spun" from a sheet of lead by passing it back and forth between revolving mandrels, each having many steel discs at short intervals; thus forming a large exposed surface in proportion to its size. The Planté type of plate is used chiefly for positives; only the Gould plate is in general use in this country as a negative true Planté plate.

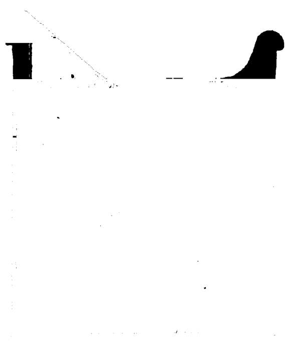


Fig 113. — "Tudor" Positive Plate.

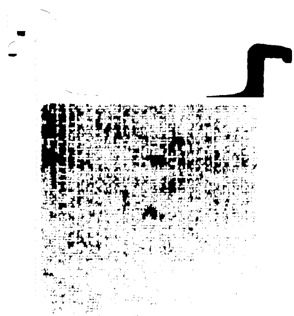


Fig 114. — "Pasted" Negative Plate.

In the Faure or pasted type of plate, the active material in paste form is spread on the surface of the plate or placed in the apertures of the grid. The paste masses used in practice

utilize the cementing action which results from the formation of lead sulphate to harden the paste. The original pasted plate as developed by Faure consisted of thin sheets of lead, roughened on their surface, over which was spread the active material. This method was not commercially successful because the active material, the lead peroxide on the positive plate, did not adhere thoroughly to the supporting grid and fell away. Many forms of grid for locking the material have been developed; they consist of antimony-lead castings of various patterns, such as the "shelf" and "diamond" type. Fig. 114 shows a pasted plate. Such plates are principally used where the greatest capacity is desired for minimum weight and space. The *box negative* plate (Fig. 115) consists of an alloy frame with a number of small openings which are filled with finely divided porous sponge lead. As this material is not mechanically self-supporting, a perforated cover is placed on each side of the frame to hold the blocks of active material in place.

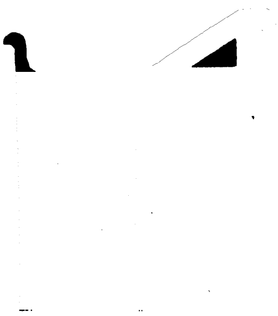


Fig. 115. — "Box" Negative Plate.

A combination of the Faure negative plate and the Planté positive plate is found in the "Chloride Accumulator" (Fig. 116) made by the Electric Storage Battery Co., which consists of a Manchester positive and a box negative. The Chloride Accumulator, as made at the present time, is "Chloride" in name only, as the active material is not made from chlorides, as it was in the original Chloride Battery manufactured at one time by

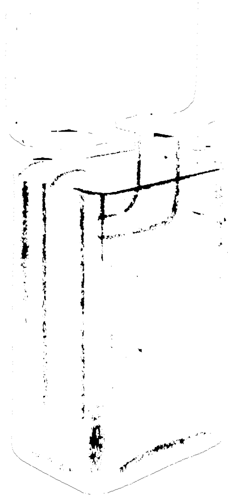
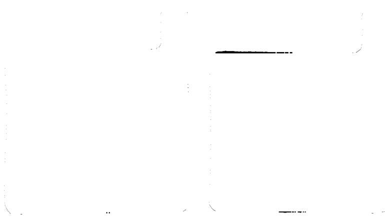


Fig. 116. — "Chloride" Accumulator.

that and allied companies abroad. This well-known trade name has been retained, though the method of manufacturing the present type of plates is entirely different.

The Gould cell, made by the Gould Storage Battery Co., for heavy duty, as for power-station service, is an example of one using the Planté type of plate for both positives and negatives.

The "Exide Battery" is manufactured by the Electric Storage Battery Co. chiefly for electric vehicle work and for starting, lighting and ignition service on automobiles. The positive and negative plates are of the Faure type, and consist of lead-antimony grids which support the active material in the form of a series of vertical strips held between the grid bars and locked in place by horizontal surface ribs that are staggered in opposite sides. After the grids are cast, they are "pasted" with oxides of lead made into a paste of special composition which sets in drying. The plates then go through an electro-chemical process which converts the material of the positives into brown peroxide of lead and that of the negative into gray spongy lead. Fig. 117 shows a finished positive and negative plate; Fig. 118 shows a complete Exide element. One of the chief features of this battery is increased power for a given weight and size, which is obtained by the use of thin



Positive Plate Negative Plate.

Fig. 117. — Plates of an Exide Storage Cell.

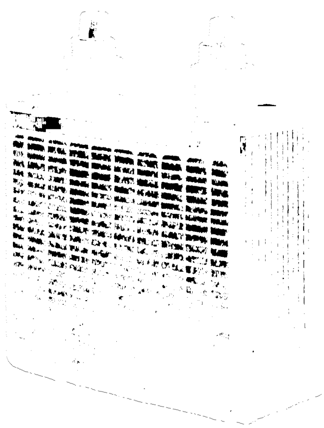


Fig. 118 — Complete Element-Exide Storage Cell.

plates of large area, yet so designed as to be rugged and long-lived.

The "Ironclad-Exide Battery" (Fig. 119), used principally for the propulsion of vehicles, is an improvement on the Exide battery in the method of holding the active material in the positive plate. This plate has a grid composed of a number of parallel vertical metal rods which are united integrally to horizontal top and bottom frames, the frame being provided with the usual conducting lug. Each vertical rod forms a core which is surrounded by a cylindrical pencil of peroxide of lead, the active material. This, in turn, is inclosed by a hard rubber tube having a large number of horizontal slits. These slits serve to provide access for the electrolyte to the active material, and yet are so fine as to practically eliminate the washing out of the material. The Ironclad-Exide negative plate is of modified Exide form; the top and bottom edges are encased in rubber, vulcanized in place. This arrangement eliminates the possibility of short-circuits from material bridging across from the positive frames.

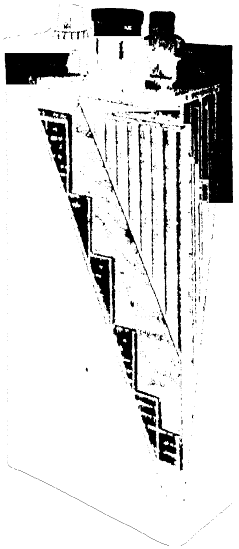


Fig. 119.— Iron-clad Exide Battery.

159. The Rated Capacity of a Storage Cell or Battery. — The capacity of a storage cell is rated in ampere-hours, ¶ 94, which is the quantity of electricity the battery will supply from a fully-charged condition when discharging at constant current for a prescribed time until its voltage has fallen to a certain value. This rating is frequently based on the so-called *normal* or 8-hour rate of discharge for the stationary type of lead-acid batteries, other types being generally based on a shorter discharge. For example, if a cell is rated as having a capacity of 200 ampere-hours, its normal rate of discharge is determined by simply dividing the rating 200 by 8, with the

result that the normal current that can be taken from the cell is 25 amperes for 8 hours. Theoretically it would seem that this cell should give a discharge of 50 amperes for 4 hours or perhaps 200 amperes for one hour. Practical experience, however, has shown that if the rate of discharge of a cell is increased its ampere-hour capacity will be decreased; thus the foregoing cell may only deliver 100 amperes at the one-hour rate. This reduction of capacity results from the inability of the acid to diffuse into the active material during quick discharges. At present there are many uses for storage batteries in which the time of discharge is much shorter than the normal 8-hour rate, and because the capacity varies with the discharge rate, it is now the custom of battery manufacturers to state the discharge current for various times. Thus a 21-plate Type F cell made by the Electric Storage Battery Company is rated to give 100 amperes for 8 hours, 140 amperes for 5 hours, 200 amperes for 3 hours and 400 amperes for 1 hour.

The capacity of a storage cell increases directly with the area of the plates exposed to the electrolyte. The capacity in practice is rated at from 40 to 60 ampere-hours (8-hour rate) per sq. ft. of exposed positive plate surface. Each cell of a storage battery of large capacity contains a number of positive and of negative plates. The positives are all connected together in one *group* to a common terminal by means of a lead strap, and the negative plates are connected in a similar group, as in Fig. 118, the two sets of plates being interleaved with each other, so that each positive plate has a negative plate adjacent to and facing it on either side. This requires one more negative plate in each cell than positives.

Problem 84. — Allowing 50 ampere-hours per square foot of positive plate surface, what is the capacity of a lead storage cell which has 12 positive and 13 negative plates, each 15 × 16 inches?

Area of positive plates = $12 \times 2 \times 15 \times 16 = 5760$ sq. in. = 40 sq. ft.

Capacity of cell = $50 \times 40 = 2000$ ampere-hours (8-hour rate).

When the positive and negative groups are assembled together, the adjacent plates, being of opposite polarity, must be kept separated and insulated from each other, as electrical contact between the two groups at any point will short-circuit the entire cell. For this reason separators are placed between

the plates to prevent contact between them, and these separators are now almost universally made of wood. The positive and negative groups, together with the separators, are collectively called the *element* (Fig. 118); the element is usually set vertically in a containing jar of hard rubber or glass, or in a lead-lined wood tank.

160. Care and Maintenance of Lead Cells. — The greatest care should be exercised in the maintenance and operation of storage batteries, for without proper care they deteriorate very rapidly. The main points to be considered in the operation of lead cells are: (*a*) the electrolyte; (*b*) rates and extent of charge and discharge.

(*a*) Only pure sulphuric acid and distilled water should be used in making the electrolyte. If the electrolyte contains other acids or small amounts of any metals but lead, the battery will be subject to local action, and complex chemical reactions will go on which may ruin the cells. Impurities may be introduced by using ordinary faucet or well water in filling cells, or by allowing metal particles to get into them. The specific gravity of the electrolyte should be kept at the figure prescribed by the manufacturer; it will probably be in the neighborhood of 1210 for the stationary types and of 1280 for the motor-vehicle types of cells when charged. Keep the level of the electrolyte above the tops of plates by filling with pure water to make up for evaporation. Never add pure sulphuric acid.

(*b*) It has been stated in ¶ 159 that the more rapid the discharge of a storage cell the lower will be its ampere-hour capacity. Properly constructed Planté plates may be discharged at almost any rate without harm if they are charged again immediately after the completion of the discharge. Avoid *overdischarge*, as this produces an excess of lead sulphate in the deeper crevices of the plates and may occasion buckling or fracture. Buckled plates should be straightened out as soon as observed. Tests of terminal voltage of the cell and of specific gravity of the electrolyte will indicate when the cell has been discharged as much as is practicable; discharge should be discontinued when the voltage falls to from 1.8 to 1.6 volts, and when the specific gravity has been lowered to from

1175 to 1185. Do not let the battery stand in an uncharged condition.

Charging of storage batteries is usually carried out at higher rates than the normal 8-hour rate; for example, a cell has its charge started with a current value corresponding to the 3-hour discharge rate, and finished with a current corresponding to the 8-hour rate. Recent rules in regard to charging indicate that well-built lead cells in good condition may be charged at any convenient rate provided that their temperature does not exceed 105° or 110° F., and that they do not produce an excessive amount of gassing at the end of the charge. *Insufficient charging and charging at low rates are to be avoided;* excessive sulphation and buckling of the plates may result otherwise. The charging of a battery should continue until (1) all its cells are gassing uniformly at both sets of plates, (2) the density of the electrolytes has reached its proper value for full charge, between 1200 and 1300, and (3) with constant charging current the voltage per cell does not rise further as determined by successive 15-minute readings. The voltage of a cell on open-circuit is of no value whatever in determining its condition of charge or discharge; voltage readings should be taken when the cell is either charging or discharging. An overcharge should be given to a storage battery weekly, biweekly or monthly depending upon the nature of its work, the duration of this overcharge being at least one hour at the 8-hour charging rate. Indiscriminate overcharge is merely a waste of electrical energy, used only in producing gases.

Cells should be kept clean. Active materials shed or fall away from the plates and accumulate in the bottom of the tank. Care must be exercised that this deposit does not rise high enough to touch and thereby short-circuit the plates. Keep the separators between the plates in good order.

The constant inspection and care of a storage battery is well repaid by its increased life. Positive plates should last from three to ten years or longer, depending on service; negatives last much longer.

161. The Nickel-Alkali or Edison Storage Cell. — The Edison Storage Cell is quite different from the lead-acid cells in electrolyte, active materials, and construction. The posi-

tive plate (Fig. 120) of the Edison cell consists of hollow perforated tubes formed of spirally-wound steel ribbon. These tubes are filled with alternate layers of nickel hydrate and pure nickel flake; the nickel hydrate is converted to nickel oxide on first charge and this is the active material, the pure nickel in very thin flakes being introduced to increase the electrical conductivity. These tubes are firmly clamped into a steel supporting grid. The negative plate (Fig. 120) consists of perforated rectangular, sheet-steel pockets, which are loaded with iron oxide mixed with a little mercury oxide to increase its conductivity. These pockets are placed in the apertures of the steel supporting grid and forced into good electrical contact under hydraulic pressure. Fig. 121 shows the plates assembled into a complete element. All metallic parts are heavily nickel-plated, and the container is a rectangular vessel of sheet steel, nickel-plated. The electrolyte is a 21-per-cent solution of caustic potash, to which is added a small amount of lithium hydrate; its density when made is from 1.20 to 1.23.

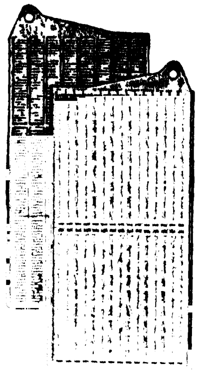


Fig. 120. — Plates of the Nickel-alkali or Edison Storage Cell

Positive plate in front, negative in back

The fundamental principle of the Edison cell is the oxidation and reduction of metals in an electrolyte which will not dissolve or combine with either the metals or the oxides. The electrolyte is decomposed by the current but is simultaneously reformed to an equal amount by a secondary action, and it remains, therefore, practically constant in density and conductivity over long periods of time, thus doing away with the

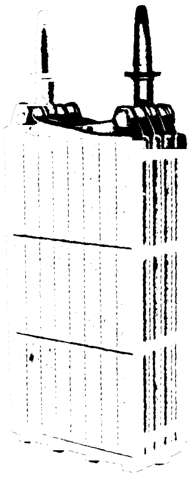


Fig. 121. — Complete Element of the Edison Storage Cell.

taking of hydrometer readings for determining the condition of the cell.

When a charging current is first passed through the cell, the nickel hydrate is changed to nickel oxide, by the oxygen that is liberated acting on the positive plate, and the iron oxide is reduced to metallic iron, by the action of the liberated hydrogen upon the iron oxide; thus the cell may be considered to consist of a positive plate of nickel oxide (NiO_2) and a negative plate of pure iron (Fe). During discharge of the cell the electrolyte of caustic potash (KOH) is broken up, the potassium (K) going to the nickel oxide and reducing it to a lower oxide of nickel (Ni_3O_4); the pure iron is changed to iron oxide (Fe_3O_4) by the liberated OH uniting with the iron. Upon again sending a charging current through the cell the plates are brought back to their original conditions. These chemical actions may be represented by the following equations:

DISCHARGE

$$\begin{array}{lll} \text{Positive} & 6\,NiO_2 + & \multirow{2}{*}{$8\begin{Bmatrix} K \\ OH \end{Bmatrix}$} + 1\,H_2O = 2\,Ni_3O_4 + 8\,KOH \\ \text{Negative} & 3\,Fe \quad + & \qquad\qquad = Fe_3O_4 + 4\,H_2O \end{array}$$

CHARGE

$$\begin{array}{lll} \text{Positive} & 2\,Ni_3O_4 + & 8\begin{Bmatrix} OH \\ K \end{Bmatrix} = 6\,NiO_2 + 4\,H_2O \\ \text{Negative} & Fe_3O_4 \quad + & \qquad + 1\,H_2O = 3\,Fe + 8\,KOH \end{array}$$

These four equations may be collected in a single expression as below, reading toward the right for charging conditions and toward the left for discharge.

$$2\,Ni_3O_4 + Fe_3O_4 + 8\,KOH + 4\,H_2O \rightleftarrows 6\,NiO_2 + 3\,Fe + 8\,KOH + 4\,H_2O.$$

The average voltage of the Edison cell during discharge is 1.2 volts, as against 2 volts of the lead-acid cell. Its cost is about twice that of the lead cell. These disadvantages, however, are offset by its ruggedness, lighter weight, great reliability, and low maintenance cost, particularly for certain classes of service, such as electric-vehicle propulsion and in train-lighting service. It will suffer no damage from subjection to such low temperatures as 40 degrees below zero F. The plates of the Edison battery will not be iniured if allowed to

stand for long periods in the electrolyte in a discharged condition. The cell should be recharged when its voltage has fallen to 0.9 volt. Evaporation of the electrolyte is compensated for by the addition of distilled water. It may be fully charged at high rates without injury.

162. Efficiency of a Storage Cell. — Not all of the electrical energy that is imparted to a storage cell during charge is recovered when it is discharged. The ratio between the energy in watt-hours taken out of a cell on discharge to the energy supplied to it on charge to bring it back to its original condition is termed its *watt-hour efficiency* (see ¶ 151). This efficiency for the lead storage battery is about 70 to 80 per cent and for the Edison battery is about 60 per cent. The efficiency of batteries which discharge only partially and for short periods, and which are then again charged, may exceed the foregoing values.

The efficiency of a storage cell may also be expressed by dividing the ampere-hour output by the ampere-hour input, which result is termed the *ampere-hour efficiency*. This efficiency, which is always higher than the watt-hour efficiency, may be as high as 90 or 95 per cent, for current is lost only by local action and by gassing at the ends of charge. Of the two efficiencies, the former or watt-hour efficiency is of commercial importance since it considers the energy relations, and includes the voltage as well as the ampere-hours. The watt-hour efficiency is lower than the ampere-hour efficiency, due to the fact that the E. M. F. on charge is higher than on discharge.

Problem 85. — A storage battery comprising 50 series-connected cells is charged at an average of 2.3 volts per cell for 8 hours, the charging current being 12.5 amperes. The cells are then arranged in two groups of 25 cells in series in each group, with the two groups connected in parallel, and joined to twenty 50-volt, 50-watt incandescent lamps in parallel. (*a*) Assuming the cells to have an ampere-hour efficiency of 90 per cent, for how long a time will the battery light the lamps? (*b*) What is the watt-hour efficiency of the battery if the cells discharge at an average of 2 volts each?

By ¶ 94 ampere-hours = amperes × hours.
Ampere-hours input = $12.5 \times 8 = 100$ ampere-hours.

Each group of 25 cells in series has a capacity of 100 ampere-hours, as the capacity of a battery is not increased by connecting cells in series;

but the capacity of the 2 groups in parallel will be $100 \times 2 = 200$ ampere-hours. Since the ampere-hour efficiency of the battery is 90 per cent, the available capacity for lighting the lamps is $200 \times 0.90 = 180$ ampere-hours. The current required for each lamp is $I = \frac{P}{E} = \frac{50}{50} = 1$ ampere, and the total current for 20 lamps is 20 amperes.

$$\text{Therefore, hours} = \frac{\text{ampere-hours}}{\text{amperes}} = \frac{180}{20} = 9 \text{ hours } (a).$$

The *input* in ampere-hours is 100, and the cells charge at 2.3 volts each; therefore *watt-hours on charge* $= 100 \times 2.3 = 230$ watt-hours. Ampere-hours *output* from the two parallel groups of cells = 180, whence the output is $\frac{180}{2} = 90$ ampere-hours from each group. Cells discharge at 2 volts, therefore *watt-hours on discharge* $= 90 \times 2 = 180$ watt-hours. Then since

$$\text{watt-hour efficiency} = \frac{\text{energy output}}{\text{energy input}} = \frac{\text{watt-hours on discharge}}{\text{watt-hours on charge}},$$

it follows that

$$\text{watt-hour efficiency} = \frac{180}{230} = 78 \text{ per cent } (b).$$

163. Methods of Charging. — The voltage required to charge a battery must be greater than the discharge voltage of the battery. Its value is found by multiplying the number of cells in a lead-acid battery by 2.5, and by multiplying the number of cells in an Edison battery by 1.75. The charging current is controlled so that the charge will take place at an appropriate rate, say between the 4-hour and 50-hour rate. Some manufacturers designate two charging rates, called the "starting" and the "finishing" rates; the latter is used to complete the charge after the cells start to gas freely. The charging current must always be sent through the battery from the positive to the negative pole, in other words, in the direction opposite to that in which the current flows through the battery during discharge. The positive pole of storage batteries is usually marked by a plus sign or the letters POS stamped on that terminal, or is painted red, and this terminal *must* be connected to the positive pole of the source of current supply. The polarity of the supply mains may be determined by means of a polarity indicator, by a voltmeter, or by dipping two wires from the supply mains in some water to which a little salt has

been added — the terminal from which the least gas (oxygen) is liberated is the positive terminal. A direct current only can be used for charging storage batteries. Where alternating current is the only available source of electricity, it must first be converted to direct current by means of a motor-generator, a converter, or a mercury-vapor or tungar rectifier. (See ¶ 367.)

For charging portable batteries from a direct-current incandescent lighting circuit where the voltage is greater than that of the battery it is necessary to insert a variable resistance in

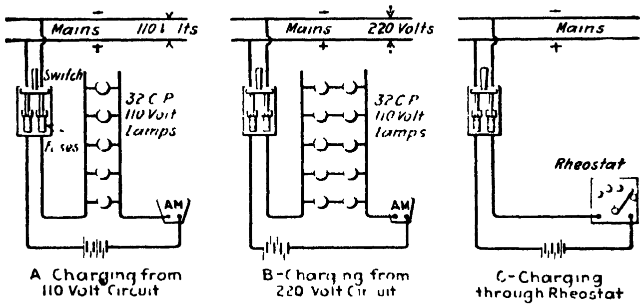


Fig. 122. Connections for Charging Small Storage Batteries.

series with the battery and the charging source in order to regulate or adjust the charging current to a suitable value. This resistance is usually in the form of lamps or a rheostat. Fig. 122A shows the connections for charging a storage battery from a 110-volt circuit, using lamps as resistance; the lamps are connected in parallel and the entire group is placed in series with the battery to the source of supply; an ammeter may be connected in series with the battery to indicate the value of the charging current. Where a bank of lamps is used, the lamps should pfeferably be of the carbon-filament type, for this type has a greater current consumption for a given amount of light than the modern tungsten-filament lamp and fewer lamps will be required to obtain any given current. Using 110-volt carbon-filament lamps, each 16-C.P. lamp will take 0.5 ampere and the 32-C.P. lamp 1 ampere; therefore. a bank of lamps having ten 16-C.P. lamps in parallel would

allow a current of approximately 5 amperes to flow through a battery from a 110-volt circuit; five 32-C.P. lamps in parallel would also take 5 amperes. In charging from a 220-volt circuit, using a lamp bank with 110-volt lamps (Fig. 122 B), there would need to be ten parallel groups of two 16-C.P. lamps in series in each group, or five parallel groups of two 32-C.P. lamps in series in each group. To charge from a 550-volt circuit there would have to be 5 lamps in series in each parallel group. When a rheostat is used instead of lamps, its resistance should be such as to produce, when carrying the proper charging current, a drop in volts equal to the difference between the pressure of the charging source and that of the battery to be charged (Fig. 122 C).

Problem 86. — How much resistance would be necessary to insert in a rheostat connected in series with a 10-cell lead battery to be charged from a 110-volt circuit, if the charging current is to be 5 amperes and the voltage across each cell is to be 2.2 volts at the beginning of charge?

Charging voltage = $10 \times 2.2 = 22$ volts. Then the voltage across the rheostat is $110 - 22 = 88$ volts.

By Formula (29) $R = \frac{E}{I} = \frac{88}{5} = 17.6$ ohms.

Problem 87. — In Problem 86, if a lamp bank resistance were used instead of the rheostat, how many 210-ohm (hot resistance) lamps in parallel would be needed to make up the desired resistance?

From Problem 86, the necessary resistance was found to be 17.6 ohms

By Formula (31) $nq = \frac{R}{J.R.} = \frac{210}{17.6} = 12$ lamps.

A departure from the foregoing method of charging is advocated by some users of lead-acid vehicle batteries, and requires the battery to be connected without resistance directly across a source of potential whose value is equal to 2.3 times the number of lead cells. This method involves no energy losses in series resistances and the batteries are charged in a short time with very little attention and without overheating and gassing. For example, a discharged Type MV "Hycap-Exide" 13-plate cell, whose starting and finishing rates are specified as 30 and 12 amperes respectively, will take the following charging currents at various times after 2.3 volts are applied to its terminals:

Time of charge in hours	*Charging current in amperes*
0	160
$\frac{1}{4}$	110
$\frac{1}{2}$	80
1	55
2	28
4	10

The battery will then be about $\frac{3}{4}$ charged and ready for almost a full day's service. It is advised to give the battery an overcharge once a week by raising the potential after the above 4-hour charging period. If the available source of potential has not the proper value, that is 2.3 times the number of cells, then a motor-generator will be required to utilize this "constant-potential" charging system, or else use may be made of counter-electromotive force cells in series with the battery; these cells occasion a constant drop of about 3 volts per cell irrespective of the charging current.

The charging of the storage batteries used in central stations and in railway service, which are used at times to carry part or all of the station load at the regular line voltage, may be accomplished from the line voltage by splitting the battery in half and connecting the two halves in parallel, or by using a booster to add a sufficient amount to the line voltage to enable all the cells to be charged in series. With large batteries automatic regulating boosters or end cells with end-cell switches are employed in charging.

164. Uses of Storage Batteries. — The uses to which storage batteries may be put are many and varied. They are used principally: in central power stations, in isolated plants, for telephone and telegraph service, for operating electric motor-driven vehicles, and for lighting steam railway cars. They are also used on nearly all the modern gasoline automobiles to furnish current in connection with a small generator for ignition and lighting and for operating the dynamo as a motor to start the engine. For this work 6 volts are common, three cells of lead-acid battery or five cells of nickel-alkali Edison battery being used. A lead starting battery of 100 ampere-hours (based on a 5-ampere discharge for lighting) has its starting

ability expressed by discharging fully at 200 amperes in 10 minutes.

Storage batteries are used in central stations in aiding the generators to carry the so-called "peaks" of the load which may occur regularly at certain periods of the day, such as the early morning and evening "rush-hours" of electric traction systems, or may happen at any time, such as an unexpected load on a lighting central station due to a mid-day storm. The battery is charged when the load on the station is light, and when an emergency arises, the battery, placed in parallel with the generators, assumes its part of the load. This arrangement is more economical than the installation of the larger generators prime movers and boilers that would otherwise be necessary to carry the peak loads.

The most important use of storage batteries in central station work is to provide an emergency reserve in case of accident to the generating machinery, when the battery may be called upon to carry the entire load of the station for a short time. Many electricity supply companies have large storage batteries called "stand-by" batteries for this emergency service so as to avoid a stoppage in service. One substation of the N. Y. Edison Co. has a battery of 150 lead cells in series which is capable of delivering 12,000 amperes at 240 volts for 1 hour, or if necessary 50,000 amperes for 6 minutes. Batteries are also used for maintaining the voltage constant at the ends of feeders or for carrying the entire load during hours of light load when the generating machinery can be shut down.

Many of the uses stated above for batteries in central station work apply equally well to batteries in isolated plants, such as found in some hotels and office buildings. Small isolated plants for lighting residences which are remote from a central station consist of a 32- or 110-volt storage battery as the main supply of current for lighting, a generator driven by a gas or gasoline engine being used to charge the battery at convenient times, and to supplement the battery when there is a heavy demand for current.

A submarine derives its entire motive power from storage batteries when submerged. Such batteries must be of large capacity but must occupy a minimum of space and be not too

heavy; in modern submarines the battery constitutes about 16 per cent of its total weight.

Batteries for train lighting furnish current for lighting the cars while they are at rest or moving slowly, while a generator driven from the car axle furnishes current for the lamps and charges the battery when proper speed is attained.

Batteries used for operating electric motor-driven vehicles consist of from 20 to 44 lead cells or 36 to 60 Edison cells; to meet the requirements of speed and current for heavy loads the battery is connected by a controller through a combination of series and parallel connected resistances for furnishing current to the motor.

QUESTIONS

1. What is the difference between a primary cell and a storage cell?

2. What does an accumulator store?

3. What are the active materials of a charged lead-acid storage cell?

4. Describe the chemical action produced in a lead storage cell by the charging current.

5. Describe the chemical action taking place in a lead cell when it is discharging.

6. What voltage should a fully-charged lead storage cell have?

7. Why is it not advisable to discharge a storage cell beyond a certain point?

8. How would you determine when a lead storage cell was fully charged, and how would you know when to stop the discharge of a cell?

9. How is the capacity of a storage cell rated, and what is it dependent upon?

10. What are the active materials in the Edison storage cell? Describe its action during charge and discharge.

11. What are the advantages and disadvantages of the Edison storage cell over the lead cell?

12. To what uses are storage batteries put?

13. How would you charge a 10-volt storage battery from a 110-volt direct-current circuit, charging rate to be 5 amperes, extra resistance to be made up of incandescent lamps? Make a sketch of connections, indicating all polarities, and the number and kind of lamps that you would use to obtain the desired current.

14. A battery is charged for 10 hours, the charging rate being 10 amperes at a pressure of 25 volts. The battery is then connected to a number of lamps requiring for proper illumination a total current of 5 amperes. (*a*) If the ampere-hour efficiency is 90 per cent, how long will the battery deliver the 5 amperes? (*b*) What is the watt-hour efficiency of the battery if the average pressure on discharge is 19 volts? *Ans.* (*a*) 18 hours; (*b*) 68.4 per cent.

LESSON XIII

ELECTROMAGNETISM

Electromagnetism — Direction of Lines of Force around a Straight Current-carrying Wire — Deflection of a Horizontal Magnetic Needle — Right-Hand Rule for Direction of Magnetic Field around Wires — Magnetic Field around a Circular Wire Carrying a Current — Magnetic Field at the Center of a Circular Current — Magnetic Polarity of a Circular Current — The Helix and Solenoid — Rules for Determining Polarity of a Solenoid — Graphical Field of a Solenoid — Questions.

165. Electromagnetism. —

Experiment 57. — Connect three or four voltaic cells in parallel, close the circuit through a heavy bare copper wire, and then plunge the wire into iron filings. The filings are attracted to all sides of the wire, as though it were a magnet. Any part of the wire will attract the filings when the current is flowing, and the attraction will be equal on all sides of the wire, Fig. 123. When the circuit is broken the filings drop from the wire.

Electromagnetism, as distinguished from magnetism in a permanent steel magnet, *is the magnetism produced around a conductor when a current flows through it.* A current of electricity through a wire is responsible for the magnetic field set up around that conductor. The fact that every wire carrying a current possesses this magnetic field, can be proved by bringing a compass needle near the wire. The magnetic field around the wire acts on the compass needle and deflects it.

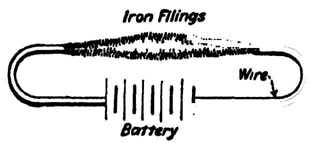


Fig. 123. — A Current-carrying Wire Attracting Iron Filings.

Experiment 58. — Pass a heavy copper wire vertically through the center of a piece of cardboard held horizontally, upper view of Fig. 124, and send a strong current through the wire. Tap the card while sifting filings upon it, and they will arrange themselves in concentric circles around the wire and at right angles to it. The plan view of Fig. 124 illustrates a graphical field made in this manner. By using paraffin paper the picture of the magnetic field may be made permanent by applying heat.

The filings are magnetic bodies free to move, and arrange themselves in the circular direction of the magnetic lines of force surrounding the wire. A compass needle held near the wire will take up a position tangent to the circular field at any point, whether the current be passed up or down the wire. The magnetic field, around a straight wire carrying a current, consists of a cylindrical whirl of circular lines, as illustrated in Fig. 125, their density decreasing as the distance from the wire increases. The circular lines of force, or *magnetic whirls*, do not merge into, cross, nor cut each other, but complete their circuits independently around the wire.

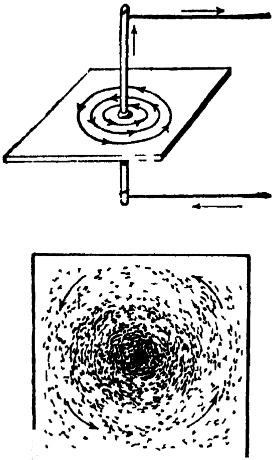


Fig. 124. — Graphical Magnetic Field of a Current-carrying Wire

Made by iron filings

166. Direction of the Lines of Force around a Straight Current-carrying Wire. –

Experiment 59. — Pass a wire vertically through a sheet of cardboard held horizontally. Arrange a number of poised needles or compasses around the wire in the form of a circle, Fig. 126, of such diameter that all the needles point nearly north and south. Pass a strong current through the wire, and note the result.

When the current flows through the vertical wire, Fig. 126, the needles, being magnetic bodies, arrange themselves around it in the direction of the circular lines of force. The **N**-poles of the needles point in the same direction as the magnetic lines of the current, and these lines pass through each of the needles, entering at the **S**-pole and emanating at the **N**-pole.

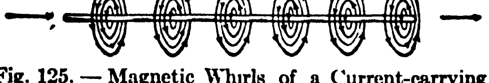


Fig. 125. — Magnetic Whirls of a Current-carrying Wire.

If the **N**-*poles of compasses placed around a vertical wire point anti-clockwise, Fig.* 126, *as you look down upon them the current is flowing toward you; if the* **N**-*poles point clockwise, Fig.* 127, *the current is flowing from you, or, in the same direction in which you are looking.*

Experiment 60. — Figs. 126 and 127 show views of the position of the needles on a horizontal piece of cardboard, with a vertical wire passed through it when the current flows in either direction. Using a single compass needle, verify the diagrams and make sketches.

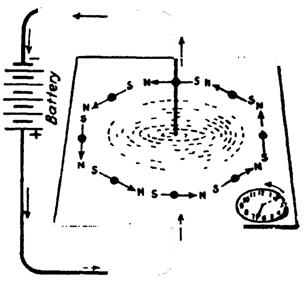


Fig. 126. — Current Flowing Up — Whirls Anti-clockwise.

The compass needles on the horizontal cardboard arrange themselves in the direction of the current's field

The fact that the needles take up a definite direction around the wire, is another reason for assuming that a current has direction. The direction of current in any vertical wire can thus be determined with a single magnetic needle, by noting the general direction that its **N**-pole points when presented to the wire.

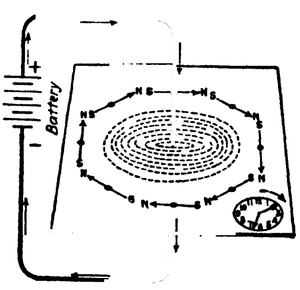


Fig. 127. — Current Flowing Down — Whirls clockwise.

167. Deflection of a Horizontal Magnetic Needle. — When a wire is held horizontally over a poised magnetic needle, pointing north and south (in the magnetic meridian), Fig. 128, and a current passed through it, the needle is deflected and tends to take up a position at right angles to the wire. When the current is sufficiently strong, the needle moves, so that it will accommodate through itself the greatest number of magnetic lines of the circular field. Considering Fig. 128, the current flows over the needle from right to left. As you look along the wire in the direction of the current the direction of the whirls is right-handed or clockwise, as indicated by the small circles around

the wire; the **N**-pole of the needle N_1 moves to the position N_2, at right angles to the wire, and in the direction of the field underneath the wire (which is from S_2 to N_2), so that the direction of the whirls and the natural lines within the needle are coincident.

Fig. 129 shows a horizontal wire carrying a current placed over or under a magnetic needle in the magnetic meridian and illustrates the direction of deflection of that needle when a current flows in either direction through the wire. Since the direction

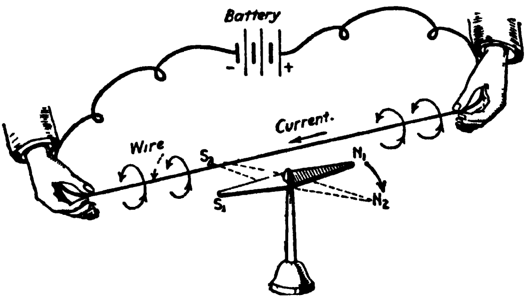


Fig. 128. – Deflection of Magnetic Needle under a Horizontal Wire Carrying a Current.

of the circular field above the wire is opposite to its direction underneath the wire the needle at B will point in the opposite direction to the needle at A. Now consider the battery terminals reversed so that the current flows from left to right as at C; the direction of the circular field is reversed and the needle under the wire will point in the opposite direction from that at A.

When a current flows from left to right in a wire placed in the magnetic meridian under a compass needle and in addition from right to left in a wire located over that needle, then the needle is deflected to an increased extent in the direction illustrated at E in Fig. 129. (Compare A and D with E of Fig. 129.) This forms a single turn, or convolution, and increasing the number of convolutions increases the extent of the needle's deflection till it assumes a position at right angles to the wire when the current is sufficiently strong. With the current

reversed in the above condition, the needle is deflected in the opposite direction. (Compare B and C with F, Fig. 129.)

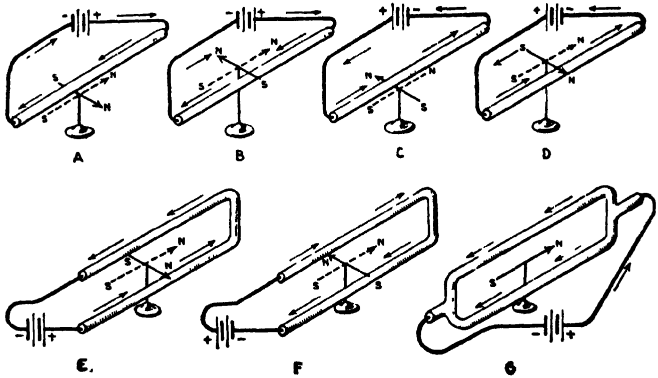


Fig. 129. — Resultant Deflections of the Magnetic Needle when Placed near to a Current-carrying Wire

The dotted arrows show the position of the magnetic needle before current flows in the wires

The current flowing in *opposite directions*, above and below the needle, *increases* the amount of deflection. Equal currents flowing above and below the needle, in the *same direction*, produce *no deflection*, (G, Fig. 129.) If two unequal currents flow, one above and the other below the needle, the needle obeys the directive force of the stronger current.

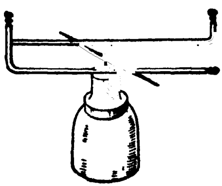


Fig. 130. — Oersted Stand for Studying the Needle's Deflection by a Current.

Experiment 61. — A simple form of apparatus for studying the relation between a needle's deflection and the direction of current, called an Oersted stand, is shown in Fig. 130. It consists of two parallel brass rods provided with binding posts and supported from a wooden base. With it the student should verify all the cases given in Fig. 129 and make sketches.

168. Right-Hand Rule for Direction of Magnetic Field around Wires. — If the direction of the current in a straight wire is known then the direction of the circular magnetic field around that wire can be determined, or vice versa. The rule follows:

Grasp the wire with the fingers of the right hand and allow the thumb to be extended in the direction of the wire as shown in Fig 131, if the thumb points in the direction of the current then the fingers indicate the direction of the lines of force around the wire

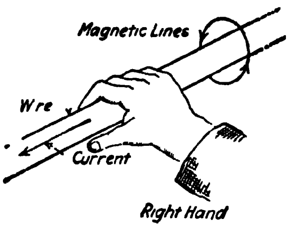


Fig 131 — Right-hand Rule for Finding Direction of Current or Direction of Magnetic Whirls

169. Magnetic Field around a Circular Wire Carrying a Current.

Experiment 62 Mount a circular turn of wire vertically in a piece of cardboard so that one half of the circle will be above the horizontal plane, as in Fig 132 Pass a current through the wire and while tapping the cardboard sift iron filings over it

The iron filings will be found to arrange themselves circularly around the wire Near the center of the loop the filings are nearly parallel with its axis If the field around the loop be explored with a compass needle it will always lie in the direction of the filings at the point chosen and its **N**-pole points in the direction of the field The arrows in Fig 132 indicate the direction of the whirls

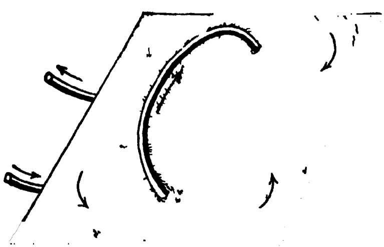


Fig 132 — Graphical Field of a Circular Current

Made with the aid of iron filings

Apply the right-hand test (¶ 168) and it will confirm the position the needles take up at any point On one side of the loop all the whirls enter it in the same direction and they emerge from the opposite side, as is further shown in Fig 133

170. Magnetic Field at the Center of a Circular Current. — If a magnetic body such as 1, Fig 133 be held above a circular loop through which a current is flowing it will tend to move downward through the loop with its axis coinciding with the axis of the loop, until its position accommodates through itself

the greatest number of lines of force of the field (¶ 20). There will be the same tendency in *B*, Fig. 134, where the current is flowing in a long rectangular circuit; but it will be seen from inspection of the two figures that many more of the lines of force due to the current act upon the magnetic body when the circuit is in the form of a circular loop than when in a rectangular or any other form. The smaller the radius of a circular loop the greater will be the strength of the field at the center of that loop for the same current in the wire Doubling the current will double the field strength.

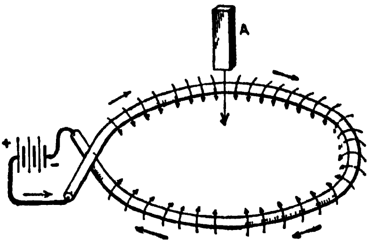


Fig 133. — Attraction of Magnetic Body A by the Magnetic Field Due to a Current Flowing in a Circular Loop of Wire.

171. Magnetic Polarity of a Circular Current. — Under the subject of Magnetism, we assumed the magnetic lines of force to pass out from the **N**-pole of a bar magnet and enter the magnet again at its **S**-pole; a similar reasoning is applied to the magnetic lines of force of an electric circuit. In the single turn of wire, Fig. 133, the current flows around the loop in the direction of the hands of a watch. The circular whirls are also clockwise, if you look along the wire in the direction of the current. The magnetic whirls, therefore, all enter the loop through its upper side, or face; consequently, this face possesses **S**-polarity, and as the same lines emanate again from the under face, that face is of **N**-polarity. The single turn of wire, therefore, possesses polarity similar to a bar magnet, and when free to move will take up a position in the earth's field with its **N**-face pointing toward the north; also, its **N**-face will be repelled by the **N**-pole of a similar loop or bar magnet, and attracted by the magnet's

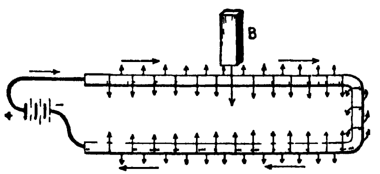


Fig. 134. — Attraction of Magnetic Body B by the Field Due to a Current Flowing in two Parallel Wires.

S-pole, according to the law of attraction and repulsion between magnets.

172. The Helix and Solenoid. — A coil of wire wound so as to follow the outlines of a screw without overlaying itself is termed a *helix* (Fig. 135) and may be wound right- or left-handed. If the current enters at the right-hand wire of Fig. 135 the magnetic field will be directed toward the left, as shown. This polarity can be reversed by rewinding the helix in the opposite direction, or by simply sending the current through the helix in the opposite direction. A *solenoid* is a coil of wire, generally wound on a wooden or other insulating spool, the length of which is usually greater than the diameter, Fig. 136. The winding is always in the same direction, layer upon layer, similar to the winding of a spool of thread. The spirals of a helix or solenoid are equivalent in their magnetic action to as many circular

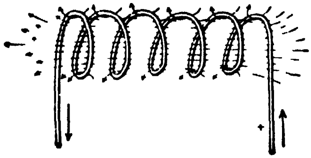


Fig. 135. — Direction of the Field of a Helix.

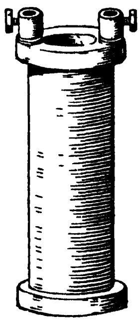


Fig. 136. — Solenoid

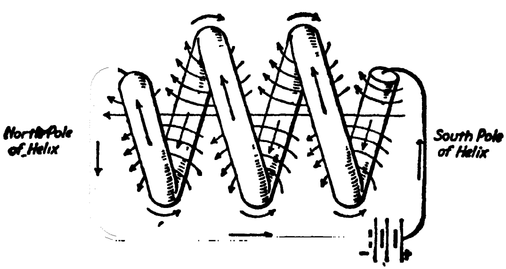


Fig. 137. — Polarity of a Helix or Solenoid.
The whirls of one turn unite with those of the next.

currents as there are convolutions of wire, since their axes lie in the same straight line. The magnetic whirls of each turn

inside the helix are in the same direction as of every other turn, and the direction of the magnetic field along and parallel to the axis of the solenoid is straight and fairly uniform to within a short distance of the ends. The total field within the solenoid is made up of the magnetic lines of the individual turns, as illustrated in the helix of Fig. 137, where the whirls of each convolution are depicted; the sum of the whirls of all the turns constituting the total field, or number of lines of force passing through the helix. This diagram shows the direction of current through the helix, the direction of the whirls around each convolution, and the resulting polarity of the helix. The action is similar for another set of convolutions wound over this set in the same direction, or for a solenoid composed of any number of layers of winding. The strength of the magnetic field of a solenoid depends upon its number of turns and the amount of current flowing in them.

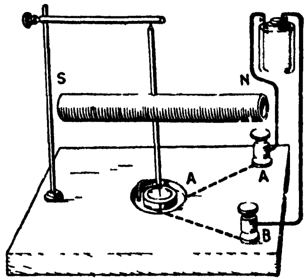


Fig. 138. — Poised Solenoid
The movable coil is poised on needle points

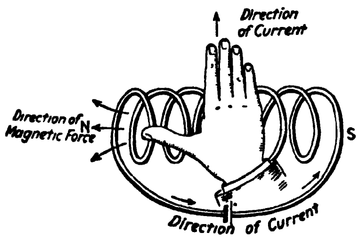


Fig. 139. — Right-hand Rule for the Polarity of a Solenoid.

Experiment 63 — Testing the Polarity of a Solenoid. — When a current is passed through a solenoid it behaves similar to a magnet. A suspended, or poised solenoid, Fig. 138, is convenient for testing the polarity. The two terminals of such a solenoid dip into two concentric circular grooves containing mercury by which contact is made. One groove is connected to each binding post by a wire, the groove stamped A corresponding with post A, so that the direction of the current may be traced. When a current is sent through the movable coil it takes up a position N-S, just as in the case of the poised needle; it is also repelled or attracted by another magnet or solenoid.

173. Rules for Determining Polarity of a Solenoid. — Clasp the solenoid, or helix, in the *right hand* so that the fingers point

around it in the direction that the current flows. The outstretched thumb, at right angles with the fingers, will point to the **N**-pole of the solenoid, Fig. 139.

To find the direction of current around the coil when the polarity is known: clasp the coil with the right hand, so that the thumb outstretched at right angles will point toward the **N**-pole, then the fingers will point in the direction of the current.

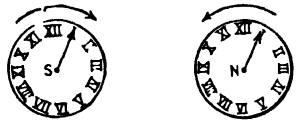


Fig. 140. — Clock Rule for Polarity.

If, on viewing the end of a solenoid, the current flows around that end in the same direction that the hands of a watch move, Fig. 140, then that end is of **S**-polarity. If the current flows around the coil against the direction in which the hands of a watch move, that end possesses **N**-polarity.

174. Graphical Field of a Solenoid. — The distribution of magnetism around a solenoid is very similar to that of a bar magnet, and can be studied by the iron filing diagram, Fig. 141.

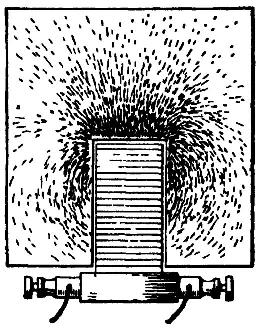


Fig. 141. — Magnetic Field of a Solenoid.

Illustrated by iron filings upon a horizontal piece of cardboard.

Experiment 64. — Cut a piece of cardboard to fit around a solenoid, as in Fig. 141. Place the cardboard horizontally so that its plane is in the axis of the coil. Pass a current through the coil, and, while gently tapping the cardboard, sift iron filings on it to produce a graphical field.

Experiment 65. — Wind a helix about 1 inch in diameter and 4 inches long. Cut a tongue in a sheet of cardboard equal to the inside diameter of the helix, and pass it horizontally through the helix with its plane in the axis of the helix. Make a graphical internal field of the helix. The direction of the lines of force may also be explored by a compass needle.

QUESTIONS

1. A feeder for an overhead trolley line is conducted up a vertical wooden pole from an underground duct. When you approach the pole from the south, the N-end of a compass needle held in your hand is deflected east. Is the current flowing up or down the pole?

2. One end of a solenoid attracts the **N**-pole of a compass needle. What is the direction of the current around the coil when viewed from this end?

3. Two parallel lines, one above the other, are stretched in a north-south direction, and equal currents flow through them in the same direction. A compass is held midway between the wires. How will its needle be affected? Make a sketch.

4. Six successive turns are made in a right-hand direction around a lead pencil, and the following six successive turns are wound in the opposite direction. A current is passed through the wire. Sketch the direction of the magnetic field you would expect to see if iron filings were used, and indicate the polarity and direction of the current.

5. A current is sent through a coil of wire wrapped around a tumbler in the same direction that the fingers of the right hand point when clasping it to drink. What is the polarity of that end of the coil you observe while drinking?

6. A current is passed through a wire held east and west over a compass needle. How will the needle be affected? Make a sketch.

7. You are given the terminals of a cable connecting with the positive and negative poles of 5 voltaic cells The terminals are to be connected so that the cells will all be in series. How would you proceed by the use of a galvanometer to determine the polarity and make the connections? Give sketch.

8. The **N**-pole of a bar magnet, lying on a table with its axis pointing east and west, deflects the **N**-pole of a compass needle 20 degrees. A wire carrying a current is held over the compass in a north-south direction and the deflection is now only 12 degrees. How do you account for this? What is the direction of the current through the wire? Make sketch.

9. An electric-light wire is run up the south wall of a building from the first to the second story. Walking toward the wire the **N**-pole of a compass held in your hand is deflected east. What is the direction of the current in the wire? Make a sketch.

LESSON XIV

ELECTROMAGNETS

Magnetization of Iron and Steel by an Electric Current — Magnetic Field of an Electromagnet — Attractive Force of a Solenoid for an Iron Core — Circuit Breakers — Magnetic Circuits — Typical Forms of Electromagnets, their Construction and Use — Polarized Electromagnets — Magnetomotive Force — Field Intensity — Law of the Magnetic Circuit — Magnetic Density, Permeability and Reluctance — Table X — Calculation of Magnetic Circuits — Magnetization Curve — Attractive Force of an Electromagnet — Questions and Problems.

175. Magnetization of Iron and Steel by an Electric Current. —

Experiment 66. — Wind a number of turns of insulated wire around an iron bar, Fig. 142, and send a current through the wire. Plunge the bar into iron filings, and it is found to attract them mostly at the ends, and when the current is interrupted the filings drop off. Test the polarity of each end of the bar with a compass. Note that upon looking at the end of the bar which repels the **N**-pole of the compass the current flows around the winding in the opposite direction to that in which the hands of a watch move (Fig. 142). When viewing that end which attracts the **N**-pole of the compass, the current flows around the wire in the direction that the hands of a watch move. Figs. 142 and 143 illustrate the polarities of a steel bar, according to the clock rule, for all possible changes in either the direction of current or the direction of winding with a given direction of current.

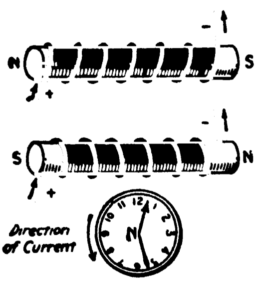


Fig. 142. — Current Anti-clockwise —N-Polarity.

Experiment 67. — Remove the bar from the coil and note that the polarity of each end of the helix is the same as with the bar inside of it; the magnetism was, however, much stronger when the bar was inserted in the coil. If suspended or poised (see Fig. 138), the helix and its iron core will take up a position in the earth's field similar to the compass needle. It will also attract or repel the poles of a like helix and core according to the law of attraction and repulsion.

When a piece of hard steel is placed in the vicinity of an electromagnetic field, many of the lines of force of the field are bent out of their natural direction and converge into the steel. There are now more lines of force passing through the space occupied by the steel than when this space was occupied by air alone. *The capability of any substance for conducting magnetic lines of force is termed its permeability;* therefore, the permeability of the steel is much greater than that of air. When a piece of soft iron is substituted for the steel, even more lines of force will pass through the same space, showing that the permeability or conducting power of iron is greater than that of steel. The permeability of iron may be several thousand times that of air, that is, several thousand times as many lines of force will pass through space when occupied by iron as when it is occupied by air. An iron bar inserted in a helix or solenoid is a much better conductor of the magnetic whirls inside the solenoid than the air, so that the strength or attractive force of the solenoid is materially increased, though the magnetizing current is the same as before. An iron core introduced into a solenoid carrying a current becomes strongly magnetized.

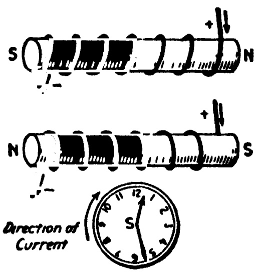


Fig. 143. — Current Clockwise — S-Polarity.

The solenoid with its core is called an *electromagnet.* The direction of the lines of force through the iron core of the solenoid is the same as their natural direction through the solenoid alone, so that all the laws for polarity of the solenoid given under Electromagnetism, Lesson XIII, apply also to an electromagnet. By applying the molecular theory of magnetism, ¶ 13, the phenomenon of magnetism in the iron bar produced by the magnetic effect of the current will be understood. The magnetic field due to the current in the wire acts inductively upon the molecules of the iron bar, causing them to change the relation of their internal magnetic circuits with respect to each other, thus producing an external field very much in the same way that a permanent magnet acts on them

The current's magnetic field simply makes evident the latent magnetism of the iron. This molecular action also accounts for the permanent magnetism produced in a piece of steel within a solenoid after the current ceases, since the internal molecular friction prevents many of the molecules from resuming their original positions.

176. Magnetic Field of an Electromagnet. — The picture of the magnetic field of a solenoid and core, or straight bar electromagnet, produced by iron filings would be similar to that of a solenoid alone, as in Fig. 141, except that the filings would be attracted more closely together, illustrating the greater density or number of lines of force due to the iron core. A compass needle, used to explore the field, will take up the same position as with the solenoid alone, but it is now affected at a much greater distance. The magnetic lines of force emanate from the N-pole of the bar electromagnet, and completing their path through the external medium enter the magnet again at its S-pole. If the iron core of the solenoid be pulled out somewhat from the coil, and filings be again applied, the magnetic lines will be found to be conducted further away from the coil before returning to it, as in Fig. 144. The polarity is still the same as before, but the poles are not so strong as when the whole internal field of the solenoid was composed of iron.

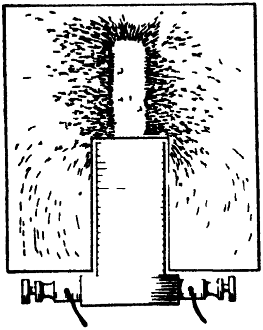


Fig. 144. — Magnetic Field of a Solenoid and Core

Shown with iron filings on a horizontal piece of cardboard

177. Attractive Force of a Solenoid for an Iron Core. — When under the attractive influence of a solenoid, an iron bar is subjected to a pull, the magnitude of which depends upon the relative position of the two bodies and the magnetizing current. If either body is free to move, and the force sufficiently strong, the body will move to accommodate through the core the greatest possible number of lines of force. This attractive force may be measured by attaching the bar to a spring balance, as shown in Fig. 145. While balanced, test

the polarity of the bar by a compass; it is magnetized by induction (¶ 21) with the polarities as shown. Note that a number of the magnetic lines from the solenoid complete their circuit through the core, entering at its upper end, which is consequently of S-polarity, and emanating from the lower or N-end to pass through the coil. Place the solenoid nearer to the core, or lower the core to it, and the pull will be considerably increased. The term "sucking coil" is sometimes applied to the solenoid when used in this way with its core. This principle is extensively applied to operate the feeding mechanism in arc lamps, to automatically open switches in electric circuits when the current becomes excessive, as in the circuit breaker, ¶ 178, to close switches at a distance for remote-control purposes, and to actuate commercial instruments for measuring current and pressure, Lesson XVII.

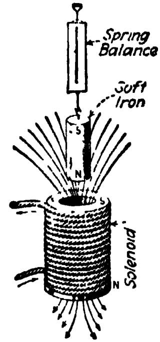
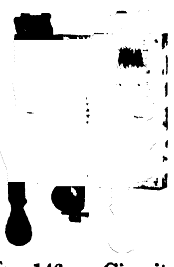


Fig. 145. — Measuring the Magnetic Attraction of a Solenoid for its Iron Core.

178. Circuit Breakers. — A circuit breaker is primarily designed to protect electrical circuits against abnormal conditions arising therein. The most usual form of circuit breakers is the plain overload type which, as its name suggests, opens the circuit in the event of overload, or excessive current. As the circuit breaker is usually made, its response to overload is almost instantaneous, but by the addition of a simply-constructed "time-limit" device, the action may be delayed so that the circuit is opened only after the overload has been carried for a brief period, this period automatically becoming less as the overload becomes greater.


Fig. 146. — Circuit Breaker.

Circuit breakers may also be equipped with a "no-voltage" device for opening the circuit when the voltage falls to a predetermined point; with a "shunt-trip" feature, for opening the circuit from push buttons placed at conveniently located

points; with a "reverse-current" arrangment, which opens the breaker upon reversal of the direction of current flow (thus affording a form of protection which is desirable where generators are operated in multiple and also for circuits from which storage batteries are charged); and with a "reversal of phase" feature for polyphase alternating-current circuits for protection against reversal of rotation of motors. In addition to the various protective features mentioned above, any of these circuit breakers may be equipped for closing as well as for opening the circuit from a remote point. This is accomplished by closing mechanisms operated by a motor, a solenoid, or compressed air.

179. Magnetic Circuits. — A simple magnetic circuit of uniform cross-section is represented by the solid iron ring

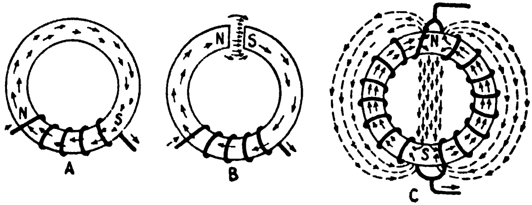


Fig. 147. — The Magnetic Polarity of an Iron Ring.

in A, Fig. 147, around which a number of turns of insulated wire have been wound. The direction of the current and the resulting polarity of the coil are shown, while the arrows indicate the direction of the lines of force around the ring. If a ring, so magnetized, be plunged into iron filings it will not show any external poles, since the magnetic lines have a complete circuit through the iron.

When a small air-gap is made by sawing out a small section of the ring (B, Fig. 147), the lines of force are compelled to pass through the air gap to complete their circuit, so that strong N- and S-poles are produced where the cut has been made, and the space is permeated with lines of force. The lines of force through the iron circuit are not nearly so dense as before, since the "resistance" of the circuit has been increased. With the same magnetizing force the magnetic lines diminish as the

"resistance" of the circuit increases, just as in an electric circuit the current decreases when, with a constant pressure, the resistance is increased. If the removed section of the ring is now replaced and the ring again plunged into iron filings while the core is magnetized, a great many filings will be attracted at the two joints, thus illustrating *magnetic leakage*. The flux density in the ring is not now so great as when it was solid, since the joints offer opposition to the magnetic lines and some of them are forced through the air across the joint.

A solid ring with two poles is shown in C, Fig. 147, the winding being in the same direction throughout the ring, and the ends of the wire being joined together. Current is sent in at any point and flows around both halves of the ring in opposite directions to a diametrically opposite point and then back to the battery. The arrows indicate the direction of current and magnetic lines of force, and it will be seen that a *consequent* **N**-pole is produced at the top of the ring and a **S**-pole at the bottom. The lines of force complete their path through the air from pole to pole, as will be noted by plunging the ring into iron filings.

Experiment 68. — Connect a horseshoe electromagnet with a source of current so that the limbs are like poles. Attract the keeper and then plunge the magnet into iron filings. One pole is produced in the center of the keeper and the opposite pole in the bend of the horseshoe. The magnetic distribution is similar to that of the solid ring with two poles in C, Fig. 147.

180. Typical Forms of Electromagnets, their Construction and Use. — If the bar electromagnet, Fig. 142, is bent around into a U shape, as in Fig. 148, it forms a horseshoe electromagnet, thereby increasing the attractive power. Instead of winding the insulated wire directly upon the core, as shown at the left, it is generally wound upon wooden or brass bobbins

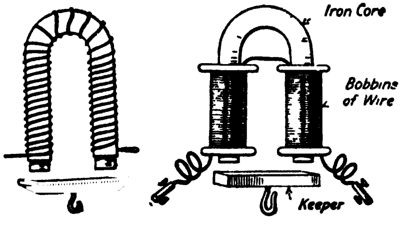


Fig. 148. — Horseshoe Electromagnets with Keepers.

several layers deep, which are then slipped over the soft iron horseshoe core, as in the right-hand view of Fig. 148. The two spools are then connected by wires so that the current will flow around the spools in the opposite directions, as viewed from the end of the core, in order that the limbs will have opposite polarity. The attractive force of the magnet may be tested by means of a keeper of adequate cross-sectional area, provided with a handle or hook.

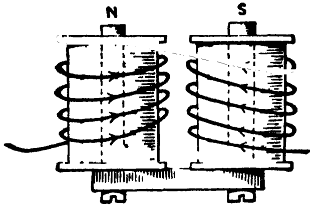


Fig. 149. — Polarity of Horseshoe Magnet for a Given Direction of Current.

Instead of a forged horseshoe the practical horseshoe electromagnet is usually made of three parts, as in Fig. 149, where the two iron cores or limbs are connected by an iron yoke of equivalent cross section and secured by machine screws. The direction of current and resulting polarity of the cores are also illustrated.

Horseshoe electromagnets are used in many practical applications of electricity, as in electric bells, automatic gas-lighting burners, telegraph sounders and relays, etc., and are designed and constructed to best perform the required service. The sounder, Fig. 150, of the telegraph consists of a horseshoe electromagnet which attracts a small soft-iron armature when a current is sent through the coils, and when the current is turned off the armature is released and pulled away from the cores by a spring. The clicks produced on attraction and release are interpreted in accordance with a telegraph code.

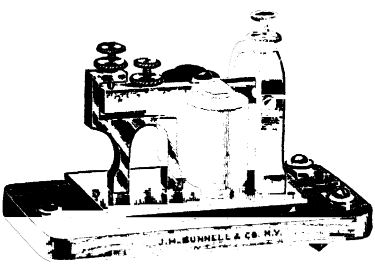


Fig. 150. — Telegraph Sounder.

A form of electromagnet that will produce a very powerful attraction at a short distance is constructed of a short cylindrical soft iron core with the proper winding upon it and sur-

rounded by an outer iron tube, the iron tube and core being united at one end by an iron yoke, Fig. 151; the iron jacket forms a return path for the lines of force and the poles are concentric. This type, known as an *ironclad*-electromagnet, is employed where a strong attraction is desired when the armature, or object it is to hold, is in actual contact with the polar surfaces. If the armature is removed a small distance from the concentric poles, there will be considerable leakage of magnetic flux between the core and outer iron jacket; therefore its use is limited to cases where the attracting distance is small. Small electromagnets of this type are used in telephone switch-board apparatus where the range of action is not great and the exciting current is of short duration.

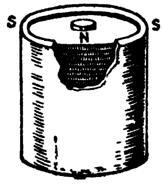


Fig. 151. — Ironclad Electromagnet

Large ironclad electromagnets are made from a solid piece of iron or steel casting, having a groove turned in the casting to receive the exciting coil. This type is well adapted for lifting purposes and many are now in use in large industrial plants for handling iron and steel of all descriptions. Fig. 152 shows a large lifting magnet of this type.


Fig. 152. — Lifting Magnet in Operation.

The lifting power of an electromagnet is proportional to the

square of the density of the lines of force per square inch and the area of the contact surface. This fact explains a peculiar phenomenon relating to lifting magnets. In an ironclad electromagnet used for lifting purposes, the greater the area of the polar surfaces and the surfaces of material to be lifted, the greater will be the attraction; but after actual contact the attraction is greater when the polar or attracting surfaces are smaller. When the area of contact is decreased the flux density (number of lines of force per unit area) through the smaller contact surfaces is increased by the lines crowding into them, and as the attractive force is proportional to the square of the density, a decrease in contact area may cause the square of the density to be increased more than the area is diminished, thus increasing the lifting power. Considering the magnet in Fig. 153 when the armature is in actual contact with the core, the attraction will be greater at the **N**-pole than at the **S**-pole.

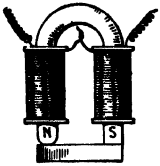


Fig. 153. — Horseshoe Magnet with Greatest Attraction at its **N**-Pole.

N-pole is smaller in area than the **S**-pole

The most important use of electromagnets is in generators and motors where they are used to create the intense magnetic fields necessary for the development of large quantities of electric power. Fig. 154 represents the field coils and the magnetic circuit of a two-pole dynamo.

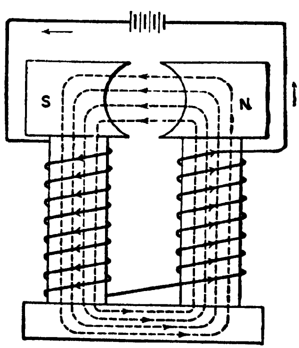


Fig. 154. — Field Coils and Magnetic Circuit of a Two-pole Dynamo.

181. Polarized Electromagnets. — A combination of a permanent magnet and an electromagnet is called a *polarized* electromagnet. In this type the whole magnetic circuit is normally under the influence of the permanent magnet alone, and when a current is sent through the electromagnet coils the polarity of the cores due to the permanent magnet may be strengthened, partly or wholly neutralized, or even reversed. This type is

extensively used in telephone ringers, Fig. 155. The magnet coils M and M′ are formed of a great many turns of fine wire wound upon soft iron cores, the cores being attached to the iron yoke Y. The soft iron armature n, pivoted at F, has the clapper rod C attached to its center so that every movement of the armature will cause the ball at the upper end of the clapper to strike the bells.

The permanent magnet N extends from the yoke, back of the coils, to a point somewhat below the armature. The armature is magnetized inductively by this permanent magnet, whose N-pole is opposite the center of the armature, and a S-pole is induced in the armature at that point, and the ends of the armature become N-poles. With no current flowing in the coils, either end of the armature will attract its adjacent magnet core. When the current flows in such direction through the electromagnet winding so as to cause the core M to become a N-pole and the core M′ a S-pole, the right-hand end of the armature will be attracted by the S-pole of the electromagnet and the other will be repelled by its N-pole, causing the armature to be tilted and moving the clapper to the left. On reversing the current, the polarity of the magnet cores will be reversed, causing the armature to be tilted in the opposite direction. When alternating current is used in ringing, the polarity of the magnet cores is reversed just as often as the direction of current in the coils is reversed, causing the armature to be tilted from one side to the other every time the current reverses, the ball of the clapper striking one of the gongs each time.

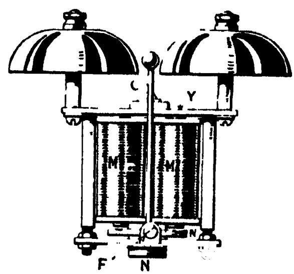


Fig. 155. — Telephone Ringer Using Polarized Type of Electromagnet.

The polarized relay illustrated in Fig. 156 and commonly used in some telegraph circuits consists of a polarized electromagnet. The permanent magnet N′S′ is of horseshoe form, and is also bent in the arc of a circle as viewed from above. The two electromagnets are mounted vertically and

carry pole pieces which face each other. Two armatures, mounted on a common shaft, are arranged so that each works between a pair of pole pieces of the electromagnet. Each armature, being pivoted near one end of the permanent magnet is inductively magnetized; assuming the end of the magnet near which the upper armature is pivoted to be of S-polarity, then the armature at that end will have N-polarity, but its other end which moves between the upper electromagnet pole pieces will be of S-polarity. Similarly, the poles of the electromagnets, being under the influence of the permanent magnet, are inductively magnetized north polarity at the upper ends and south at the lower ends, that is when they are not neutralized or reversed by current flowing through the electromagnet windings. Therefore, with no current flowing through the electromagnet, the armatures (having no directive springs) when placed midway between the electromagnet poles will be attracted equally by them; the field of the permanent magnet tends to hold the armatures in a balanced position, so that the armatures may be moved in either direction at will, according to the direction of current through the electromagnet.

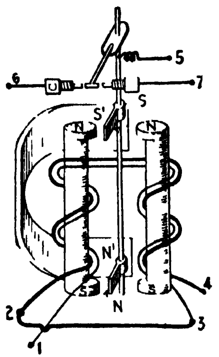


Fig. 156. — Construction of Polarized Relay.

There are two windings on the electromagnet, namely 1–3 and 2–4, which may be connected in series or in parallel as preferred; they are connected in series in Fig. 156. When the electromagnet is energized by a current entering at terminal 1 the magnetism thus produced in its cores increases the N-polarity of the left upper pole and weakens the right, it also increases the south polarity of the left lower pole and weakens the right; thus both armatures are attracted by the strengthened left-hand poles and contact is made between the tongue contact 5 and contact screw 6. The armature in polarized relays used for unidirectional current instead of being balanced is held by means of a spring toward one pole of the electromagnet, and a current of proper polarity will move the armature to the opposite pole.

182. Magnetomotive Force. —

Experiment 69. — Connect the coils of an electromagnet wound with many turns of wire in series with another magnet wound with a few turns of wire and join them to a battery. Plunge each magnet into iron filings The magnet wound with many turns attracts more filings yet, since they are in series, the current strength is the same through each magnet. The magnetism depends upon the number of turns, as well as upon the current.

Experiment 70. — Note the pull required to detach a keeper from the poles of its magnet when the spool, wound with 400 turns of fine wire, has 1 ampere passed through it. Now substitute another spool wound with 10 turns of much larger wire through which 10 amperes are sent. It will be observed that the keeper is detached by the same force as before.

From the above experiments it will be seen that the magnetism, or magnetic flux (total number of lines of force), depends upon the turns as well as upon the current strength; the current and number of turns being jointly responsible for the force that drives the magnetic flux around the magnetic circuit, just as an electromotive force drives an electric current around an electric circuit. The magnetizing force set up by a current flowing through a solenoid or any coil of wire is called the *magnetomotive force* (abbreviated *m.m.f.*); it is directly proportional to the current and to the number of turns in the solenoid. The magnetomotive force is, therefore, proportional to the product of the number of turns and the current strength. If the latter be in amperes, the magnetomotive force may be expressed in a unit called the *ampere-turn*.

TO FIND THE MAGNETOMOTIVE FORCE OF A COIL IN AMPERE-TURNS:

Multiply the number of turns upon it by the strength of current passing through it.

For example: four amperes circulating 25 times around a coil produce a magnetomotive force of 100 ampere-turns. The same force could be produced by 2 amperes and 50 turns, or by 100 amperes and 1 turn, etc., the product of the turns and current in each case being 100.

Let I = current in amperes,
T = number of turns on the coil.

Then the magnetomotive force is

$$\text{ampere-turns} = I \times T \quad . \quad . \quad . \quad . \quad (68).$$

Like results may be accomplished by magnets wound with coarse wire or with fine wire; each type has its advantage according to the manner in which it is to be used. The magnets of an electric bell, telephone, or telegraph instrument are wound with fine wire, as they are usually located at some distance from the battery, so that the current may be very small, and the line small in area, the required magnetizing force being produced by a small current flowing through a large number of turns. When it is desired to operate a small magnet from a 110-volt circuit it is wound with fine wire, so that its resistance will be high and the current requirement small, thus making it inexpensive to operate. The same magnetic pull could be obtained with a coarse wire magnet in the latter case, using a large current, at an increase in the cost of operation. Electromagnets operated in series, as in arc lamps, circuit breakers, etc., are wound with coarse wire, having a low resistance, since the whole current passes through the coil, the magnetizing force being produced by a large current and few turns.

It is necessary to express the magnetomotive force in terms of magnetic units, as follows: It has been found by experiment that one ampere-turn will produce 1.257 lines of force through an air-path one centimeter in length and one square centimeter in cross-sectional area; one ampere-turn will also produce nearly 3.2 lines of force through an air-path one inch long and one square inch in cross-sectional area. The total magnetizing force, or magnetomotive force, expressed in magnetic lines through a one-inch cube of air equals, then, the ampere-turns multiplied by 3.2, or the magnetomotive force in magnetic units is

$$\text{m. m. f.} = 3.2 \times I \times T \quad . \quad . \quad . \quad . \quad . \quad (69).$$

Thus, if we had a solenoid wound with 50 turns of wire and a current of 2 amperes flowing around them, the magnetic pressure would equal $3.2 \times 2 \times 50 = 320$ magnetic units. The above value of m. m. f. represents the magnetic pressure for the total length of the core of the solenoid or coil.

183. Field Intensity. — In magnetic calculations the magnetomotive force per unit length of the magnetic circuit is of great importance, and is called the *intensity of the magnetic*

field. This field intensity is the magnetomotive force divided by the length (l) of the magnetic path, and is represented by the letter $\mathcal{H}$. It was pointed out in ¶ 182 that one ampere-turn produces 1.257 lines of force through a cube of air one centimeter on a side. Therefore, the field intensity is

$$\mathcal{H} = \frac{\text{m. m. f.}}{l} = \frac{1.257 \times I \times T}{l}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (70).$$

where l is the length of the path in centimeters.

If the length (l) of the magnetic path of a solenoid is known, the m. m. f. necessary to produce a desired field intensity ($\mathcal{H}$), is obtained by multiplying $\mathcal{H} \times l$.

For example: suppose we have a coil of 25 turns, the coil being bent in a circular shape to form a complete ring, Fig. 147, so there will be no free poles. Each line of force would have a complete path inside the coil, so that the length of the magnetic circuit can easily be measured. A current of 20 amperes flowing through the coil would give, by Formula (68), a magnetizing force in *ampere-turns* of 500. If the mean length of the magnetic circuit is 12.5 centimeters, then the magnetomotive force per centimeter length, by Formula (70), becomes

$$\mathcal{H} = \frac{1.257 \times I \times T}{l} = \frac{1.257 \times 20 \times 25}{12.5} = 50.2,$$

meaning that a uniform magnetic field is produced in the solenoid of 50.2 lines per square centimeter, or $50.2 \times 2.54 \times 2.54 = 324$ lines of force per square inch of sectional area. The above is true only for a solenoid with a core of air or other *non-magnetic substance*.

The two formulæ just given for determining the values of $\mathcal{H}$ and m. m. f. are very similar and the distinction between them should be kept clearly in mind. The quantity $\mathcal{H}$ represents the force magnetizing a unit length of the core of a solenoid, or the strength of field in lines of force per square centimeter or per square inch, within a coil with an air core. The quantity m. m. f. represents the force (magnetic pressure) that tends to drive the lines of force throughout the entire path of any kind of material.

184. Law of the Magnetic Circuit. — Just as electric pressure (E. M. F.) is the force that moves electricity through an electric circuit, so magnetic pressure (m. m. f.) is the force that drives lines of force through a magnetic circuit. All magnetic substances offer some opposition to the passage through them of magnetic lines of force. This opposition, or magnetic "resistance," is termed *reluctance,* the symbol for which is $\mathcal{R}$. The *total number* of lines of force set up in a magnetic substance is termed *magnetic flux.* Magnetic flux, or total number of lines of force, is treated as a *magnetic* "current" flowing in the magnetic circuit.

The calculation of the magnetic flux, which we will represent by the letter N, is similar to the calculation of current in an electric circuit by Ohm's Law. In an electric circuit the strength of the electric current equals the E. M. F. ÷ resistance, that is $I = \frac{E}{R}$; in a magnetic circuit the number of magnetic lines of force which pass through it is equal to the m. m. f. ÷ reluctance, or

$$\text{magnetic flux} = \frac{\text{magnetomotive force}}{\text{reluctance}}.$$

or

$$N = \frac{\text{m. m. f}}{\mathcal{R}} \quad \ldots\ldots\ldots\ldots \quad (71).$$

This equation is analogous to the expression for Ohm's Law and on this account is frequently styled the "Ohm's Law of the magnetic circuit."

185. Magnetic Density, Permeability and Reluctance. — It is sometimes necessary to specify the flux density in any part of a magnetic circuit, that is, the number of lines passing through a unit area measured at right angles to their direction, whether that part of the circuit is air or some other material. This number is termed the *magnetic density* or *magnetic induction* of the substance, and is denoted by the letter $\mathcal{B}$. If the total flux N is known, and the area A through which it is uniformly distributed is also known, then the flux density is given by

$$\mathcal{B} = \frac{N}{A} \quad \ldots\ldots\ldots\ldots \quad (72).$$

If the area of cross section of the substance A be expressed in square inches or square centimeters, the flux density will be the number of lines per square inch or per square centimeter respectively.

The magnetic density produced in *air* by a solenoid depends entirely upon the intensity of the magnetic field (¶ 183). The magnetic density or induction $\mathcal{B}$ produced in a *magnetic* substance when placed in a solenoid depends upon one other factor, namely, the *permeability* of the substance.

The permeability of a magnetic substance is the ratio of the magnetic density $\mathcal{B}$ in the substance to the intensity of magnetic field $\mathcal{H}$ acting upon the substance; that is, a ratio of the number of lines of force per unit area, set up in the material, to the number that would be set up in air under the same conditions. The symbol for permeability is the Greek letter μ (pronounced mu), and its value for any magnetic substance is expressed in the equation

$$\mu = \frac{\mathcal{B}}{\mathcal{H}} \quad \ldots\ldots\ldots\ldots \quad (73).$$

If the value of μ and $\mathcal{H}$ are known, the magnetic density is

$$\mathcal{B} = \mu \times \mathcal{H}.$$

The permeability of air or *non-magnetic* substances is unity or 1; since through air the flux density $\mathcal{B} = \mathcal{H}$, or $\frac{\mathcal{B}}{\mathcal{H}} = 1$.

For soft iron under a field intensity $\mathcal{H} = 10$ (this corresponds by Formula (70) to 20.3 ampere-turns per inch), the flux density is $\mathcal{B} = 14{,}000$ lines per sq. cm., and consequently the permeability is $14{,}000 \div 10 = 1400$.

In magnetic materials the value of the permeability does not remain the same for all flux densities; this variation of permeability is shown in Table X.

The reluctance of a magnetic circuit depends upon three quantities: the *length* of the circuit, the cross-sectional *area* of the circuit, and the *permeability* of the material which forms the circuit. The reluctance *increases* as the length of the magnetic circuit increases, and *decreases* as the cross-sectional area

Table X. Permeability Table

Flux Density		Permeability		
Lines per square inch	Lines per square centimeter	Annealed sheet steel	Cast steel	Cast iron
20,000	3,100	2600	1400	280
30,000	4,650	2900	1500	230
40,000	6,200	3100	1400	160
50,000	7,750	3200	1350	110
60,000	9,300	3100	1250	80
70,000	10,850	2400	1100	65
80,000	12,400	1800	750	50
90,000	14,000	1400	500	
100,000	15,500	750	280	
110,000	17,400	320	145	
120,000	18,600	160	70	
130,000	20,150	75		

is increased and as the permeability increases. That is, the reluctance is directly proportional to the length of the magnetic circuit, is inversely proportional to the cross-sectional area, and varies with the material of the circuit.

Letting $\mathcal{R}$ represent the reluctance, l the length of magnetic circuit in inches, A the sectional area of the circuit in square inches, and μ the permeability of the material constituting the circuit, then

$$\mathcal{R} = \frac{l}{A \times \mu} \quad \ldots\ldots\ldots\ldots \quad (74).$$

186. Calculation of Magnetic Circuits. — The magnetic circuit is usually a compound one; that is, one composed of two or more substances; part of the magnetic path may be an air-gap which would materially increase the reluctance. It is, therefore, necessary to calculate separately the reluctance offered by each substance. The total reluctance is the sum of the separate reluctances of the various substances. Before the reluctance of any substance included in the magnetic circuit can be calculated, it is necessary to know the permeability of the substance. The permeability depends not only

upon the kind and quality of the substance, but also upon the density $\mathcal{B}$ of the lines of force. The total induction (magnetic flux N) and the dimensions of the magnet having been determined, the value of the induction $\mathcal{B}$ for each substance is found by Formula (72), $\mathcal{B} = \frac{N}{A}$. From a table or curve giving the value of $\mathcal{B}$ and $\mathcal{H}$ for different magnetic substances, the permeability may be calculated by taking the ratio $\mathcal{B} \div \mathcal{H}$, or the permeability may be taken directly from Table X of ¶ 185.

Having determined the permeability for each substance, the reluctance of each substance can be calculated, and then the total reluctance. The total reluctance $\mathcal{R}$ of the entire magnetic circuit having been determined, and the total number of lines of force or magnetic flux N having been established in the beginning by the requirements of the magnet, it becomes necessary to determine the ampere-turns required to drive the magnetic flux around the magnetic circuit. Since magnetic flux $= \frac{\text{m. m. f.}}{\mathcal{R}}$, the m. m. f. would equal $N \times \mathcal{R}$, and as m. m. f. = ampere-turns × 3.2 (¶ 182), it follows that the ampere-turns required to drive a given magnetic flux through a magnetic circuit would equal

$$\text{ampere-turns} = \frac{N}{3.2} \times \mathcal{R} \quad . \quad . \quad . \quad . \quad (75).$$

Problem 88. — Fig. 157 gives the dimensions in inches of a cast steel horseshoe core and keeper, separated by an air gap of one-quarter of an inch; the dotted line represents the total length of the magnetic circuit. Find the reluctance of each part of the magnetic circuit and the ampere-turns required to drive 40,000 lines of force through that circuit.

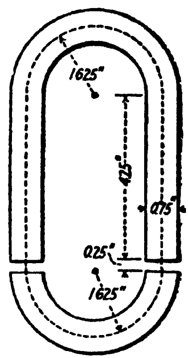


Fig. 157. — Horseshoe Core and Keeper.

Lengths of both limbs of core up to curved portion = 4.25 × 2 = 8.5 inches. Since the circumference of a circle = diam. × 3.1416, or radius × 2 × 3.1416, the length of the curved portion of the core is one-half the circumference = radius × 3.1416 = 1.625 × 3.1416 = 5.105 inches. Then, the total length of core is 8.5 + 5.105 = 13.605 inches.

Area of the round core of diameter d = 0.75 inch is $d^2 \times 0.7854 = 0.75 \times 0.75 \times 0.7854 = 0.441$ sq. in.

$$\text{Induction} = \mathfrak{B} = \frac{N}{A} = \frac{40,000}{0.441} = 90,700 \text{ lines of force per sq. in.}$$

From Table X the permeability μ for cast steel at a flux density of 90,700 is about 500.

Then, reluctance of core:

$$\mathfrak{R} = \frac{l}{A \times \mu} = \frac{13.605}{0.441 \times 500} = 0.062.$$

Reluctance of both air gaps:

Total length of gaps = 0.5 inch (each gap 0.25 inch).

Area of air path is taken the same as of core, namely 0.441 sq. in.

μ for air = 1. Then,

$$\mathfrak{R} = \frac{l}{A \times \mu} = \frac{0.5}{0.441 \times 1} = 1.133.$$

Reluctance of keeper: keeper is bent to the same radius as upper part of horseshoe; therefore, its length is the same as that part. The cross-sectional area of the keeper is the same as the core; therefore, the value of $\mathfrak{B}$ and permeability is the same, since it is of the same material. Thus the reluctance of the keeper is

$$\mathfrak{R} = \frac{l}{A \times \mu} = \frac{5.105}{0.441 \times 500} = 0.023.$$

Total reluctance = 0.062 + 1.133 + 0.023 = 1.218.

Then,

$$\text{ampere-turns} = \frac{N}{3.2} \times (\text{total } \mathfrak{R}) = \frac{40,000}{3.2} \times 1.218 = 15,230 \text{ ampere-turns.}$$

187. Magnetization Curve. — Unlike the constant resistance offered by a piece of copper to different strengths of an electric current, the reluctance of a piece of iron varies with each density of the lines of force accommodated through it, and this variation bears no constant ratio to the number of lines of force passing through it. For this reason *curves of magnetization* are constructed for different specimens of iron showing the relation of the induction to the field intensity at different stages of magnetization. Fig. 158 shows magnetization curves of steel and iron, the curves gradually sloping upwards with increased exciting current until the saturation point is reached, when the curves slope off to the horizontal.

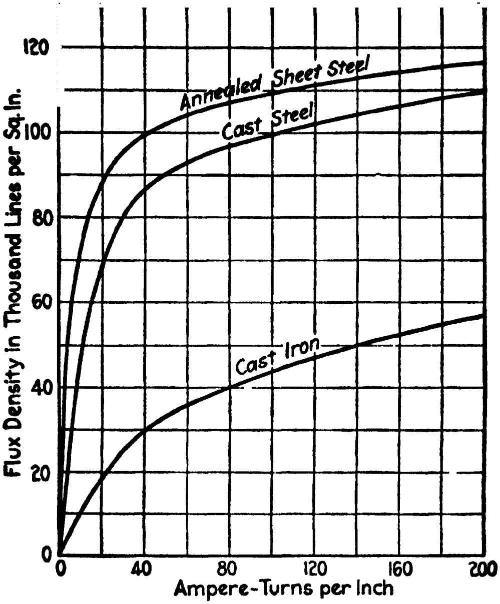


Fig. 158. — Magnetization Curves of Steel and Iron

With a given magnetizing force in ampere-turns the induction may be found from the curves

188. Attractive Force of an Electromagnet. — The magnetism of an electromagnet increases as the current through it is increased, up to the saturation point (see ¶ 15), but is not directly proportional to the current; that is, if one ampere through a certain magnet requires a force of 56 pounds to detach its keeper, then when 2 amperes are passed through it, not twice the force, or 112 pounds, is required, but usually much less. To make a test of the effect of different current strengths upon the attractive

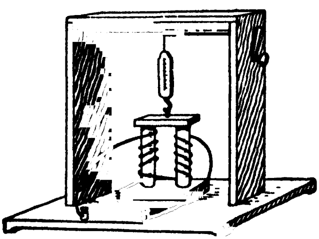


Fig. 159. — Testing the Attractive Force of an Electromagnet.

power, the magnet and keeper may be arranged in connection with a spring balance and windlass, as shown in Fig. 159. When the crank is turned the pounds pull may be noted till the detachment of the keeper takes place.

The lifting or adhesive power of an electromagnet is called its *tractive force*. The tractive force is proportional to the square of the density of lines of force per square inch, and the area of the surface contact. To determine the tractive force or "pull," in pounds, of an electromagnet, let

$\mathcal{B}$ = flux density or lines of force per square inch,
A = area of contact in square inches.

Then, the pull in pounds is

$$P = \frac{\mathcal{B}^2 \times A}{72,134,000}.$$

For example: suppose a density of 45,000 lines of force per square inch to be produced in an electromagnet by the magnetizing force. What would be the pull required to detach its keeper if the poles of the magnet had a total area of 1 square inch?

$$\mathcal{B}^2 = 45,000^2 = 2,025,000,000, \quad A = 1 \text{ sq in}; \text{ then,}$$
$$\text{Pull} = 2,025,000,000 \times 1 \div 72,134,000 = 28 \text{ pounds.}$$

Due to *magnetic leakage*, that is, some of the magnetic lines completing their path through air instead of through the keeper, the actual pull will be less than the pull calculated above.

QUESTIONS

1. The pole of an electromagnet having a soft steel core deflects a compass needle 44 degrees when held at a distance of one foot. A soft iron core is substituted for the steel and the deflection is now 58 degrees. How do you account for this, since neither the distance nor the current strength is altered?
2. Define magnetic permeability.
3. Which magnet core mentioned in Question 1 possesses the greater permeability?
4. Wind a steel key ring with insulated wire so that when a current is sent through the windings the ring will possess two diametrically opposite poles. Illustrate by sketches the direction of winding, direction of current, and direction of the magnetic lines of force. What kind of poles are produced in the key ring?

5. What is reluctance? How does the magnetic reluctance of air compare with that of iron?

6. The magnetomotive force of a solenoid is doubled. How would this affect the number of lines of force threading through it when the solenoid possesses a brass core? A soft iron core?

PROBLEMS

1. Calculate the reluctance of a non-magnetic rod 10 inches long and $\frac{1}{2}$ inch in diameter. *Ans.* 51.

2. Three relays are adjusted to operate on 250 ampere-turns, and have the following constants: —

Relay A — 2400 turns, 20 ohms resistance;
Relay B — 4500 turns, 75 ohms resistance;
Relay C — 7500 turns, 150 ohms resistance.

If these relays were connected in series across a 20-volt battery, which relays would operate?

3. What voltage would cause all three relays of Question 2 to operate? *Ans.* 25.5 volts.

4. Calculate the ampere-turns to be placed on a wrought-iron horseshoe electromagnet to produce a flux of 100,000 lines of force through it, the shape of the magnet being shown in Fig. 157 and its linear dimensions being just double the values given in that figure. Assume a gap of $\frac{1}{4}$ inch between magnet core and keeper, and use the permeabilities listed in Table X for sheet steel. *Ans.* 9050 ampere-turns.

5. What flux density will a magnetizing force of 50 ampere-turns per inch produce in cast iron? In annealed sheet steel?

6. Design a horseshoe electromagnet of wrought iron that will exert a pull of 100 pounds when traversed by a current of 2 amperes. Assume a flux density of 90,000 lines per square inch, and use the magnetization curve for sheet steel in Fig. 158.

LESSON XV

ELECTRODYNAMICS

Reaction of a Current-carrying Wire on a Magnet — Automatic Twisting of a Current-carrying Wire around a Magnetic Pole — Rotation of a Current-carrying Wire around a Magnetic Pole — Electrodynamics — The Magnetic Fields of Parallel Currents — Laws of Parallel Currents — Currents in Conductors at an Angle with Each Other — Questions.

189. Reaction of a Current-carrying Wire on a Magnet. — Every action is accompanied by an equal and opposite reaction, or, "action and reaction are equal and opposite." For example, elongate a spring in one direction by applying a force of one pound; the spring also exerts an equal force in the opposite direction, or else it would break. A ship displaces an amount of water which is equal to its own weight; the force of buoyancy is, therefore, equal and opposite to the weight of the ship, or else it would either rise or sink until equilibrium is established.

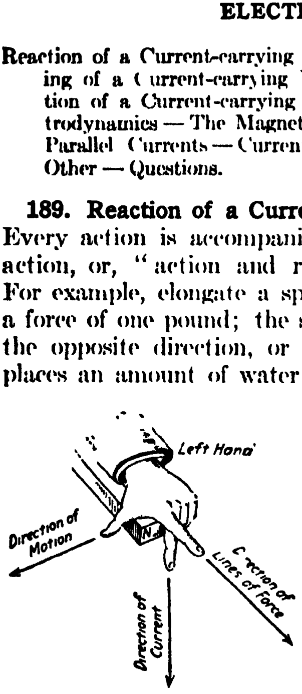


Fig. 160. — Left-hand Rule for Determining the Direction of Rotation of a Moving Wire in a Magnetic Field.

This rule applies to motors

In Lesson XIII it was shown how a magnet was deflected by the field of a wire carrying a current. When the current flows over the needle, say from north to south, and the needle is *free to move*, the **N**-end is urged by the current's field to the east and the **S**-end, to the west. Since the field of the wire reacts on the magnet's field, the magnet's field also reacts on the field of the wire, and if the wire were free to move, it would deflect in the opposite direction to that of the magnet.

In ¶ 168 the right-hand rule was given for the direction of the magnetic lines around a wire or the direction in which the needle would turn. The following rule employing the left hand will indicate the direction that the wire will move when the magnet is stationary.

Place the thumb, first and second fingers of the left hand all at right angles to each other, as in Fig. 160, and the hand so that the first finger indicates the direction of the lines of force of the magnet and the second finger the direction of the current in the wire; the thumb will then indicate the direction of motion of the wire.

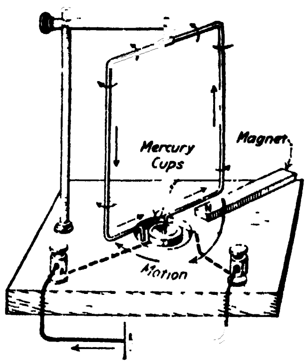


Fig. 161. The Movable Current-carrying Coil is Repelled by the Stationary Bar Magnet.

Experiment 71. — Insert a rectangular coil having a single turn of wire in a suitable frame as shown in Fig. 161. Place the horizontal portion of the coil in the magnetic meridian, and by the use of a pocket compass find the direction of current around the wire. Open the circuit and lay a bar magnet on the base, arranged so that the current flows over it from north to south, as in Fig. 161. The magnet is now stationary and the wire free to move. When the current flows the wire is deflected west Apply the left-hand rule just given to this case.

Experiment 72. — Explore the magnetic field both inside and outside of the rectangular coil by noting how the wire moves when the magnet is brought into its vicinity. The wire tends to move in all cases to such a position that its own lines of force are in the same direction as those of the field of the magnet.

190. Automatic Twisting of a Current-carrying Wire around a Magnetic Pole. — That a wire tends to move so that its magnetic field will be in the same direction as the lines of force of the magnet's field is further demonstrated as follows: a bar magnet is clamped vertically in a stand and raised several inches from the table (Fig. 162), a connector is clamped above it, and a piece of tinsel wire (which is a very flexible conductor) is supported from the connector and joined to a battery. When the current is sent up the wire from A to B, the wire twists or winds itself around the magnet in a left-hand spiral.

so that the current circulates around the magnet anti-clockwise as viewed from the N-pole end. The current, therefore, tends to increase the magnetism of the magnet and the lines of force of both are in the same direction. When the current is reversed, the tinsel unwinds and again twists itself around the magnet in a right-hand spiral. or so that the polarity of the magnet is increased by the current's field as before.

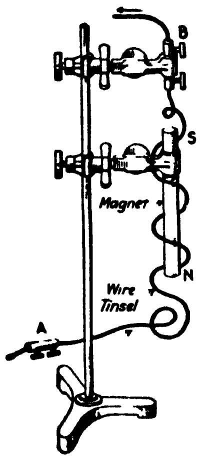


Fig 162. — The Flexible Tinsel Wire Winds around the Magnet when a Current is Sent through It.

191. Rotation of a Current-carrying Wire around a Magnetic Pole. — Since the tendency of a magnet is to urge a wire carrying a current to a position at right angles to it, continuous rotation of the wire can be produced if the wire be arranged free to move in such a manner that it will never attain such a position. In Fig. 163 a wooden ring, with a groove turned in it for the reception of mercury, is mounted above an electromagnet. One end of a piece of copper wire, AB, is hooked onto the stationary horizontal brass arm, which is supported by the vertical rod as depicted. The other end of the copper wire dips into the mercury trough which serves to complete the circuit of the current through the electromagnet.

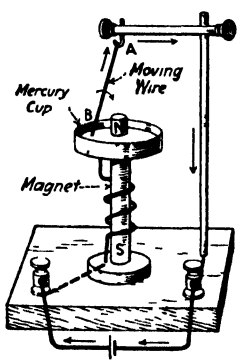


Fig. 163. — Rotation of a Current-carrying Wire around a Magnet Pole.

The magnetic field of the electromagnet is nearly at right angles to the wire, and the wire rotates about the pole when the current is passed through it. The direction of rotation can be determined before the current is turned on by the *left-hand rule* of ¶ 189. Applying this rule we find that the wire will rotate in the direction opposite to the hands of the clock. It tends to

wind around the pole in such a direction as to increase the magnetism of the pole, just as in the "automatic twisting" experiment (¶ 190).

This rule is very convenient for determining the direction of rotation of motors (¶ 284). The moving wire in Fig. 163 is analogous to the armature of the motor, and the electromagnet, its field. If the direction of current through the armature and field of Fig. 163 be reversed, as by changing the binding post terminals, the direction of rotation will be the same as before, because the current through the moving wire and the polarity of the field are both reversed, therefore, the same relation exists as before, which can be proved by the left-hand rule. If, now, only the current in the wire be reversed, or only the polarity of the field, then the direction of rotation will be reversed. Therefore, to reverse the direction of rotation of a motor, *reverse the direction of current either through the armature or through the field magnets, but not through both.*

A permanent magnet can be substituted for the electromagnet in Fig. 163, as the same principles are involved. The wooden ring could be lowered to the middle position of the magnet and the wire prolonged, in which case a greater part of its field would be in the magnet's field. If the ring were located on the base (Fig. 163) and the wire, AB, extended the whole length of the magnet, one pole would tend to urge it in one direction and the other pole in the opposite direction, so that with the poles of equal strength the wire would not rotate.

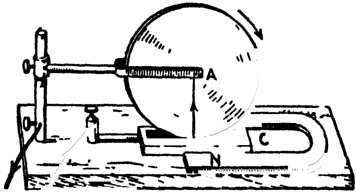


Fig. 164. — Barlow's Wheel.
Faraday's disk dynamo driven as a motor

Another device to produce continuous rotation is illustrated in Fig. 164, and is called Barlow's wheel. The edge of a pivoted copper disk dips into a trough of mercury, C, located between the poles of a horseshoe magnet, and current is sent through the disk in a radial direction, as shown. The magnet's field acts at right angles to the current's field, since the current flows from the periphery of the disk to its axis, A,

and the disk will rotate in the direction of the hands of a clock (Fig. 164); this statement can be verified by the left-hand rule.

192. Electrodynamics. — The term *electrodynamics* is applied to the study of that part of electricity which treats of the force exerted by one current upon another. We have just noted the reciprocal action between a current and a magnet, and now in electrodynamics, the mutual action of the currents upon each other is to be considered. Every wire through which a current is flowing is surrounded by a magnetic field,

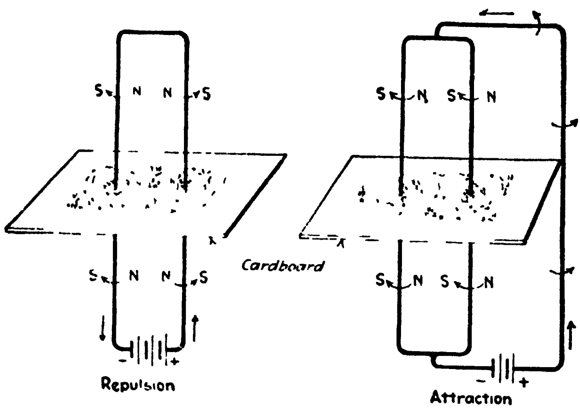


Fig. 165. — Parallel Currents Flowing in the Same Direction Attract Each Other; if in Opposite Directions they Repel Each Other.

and the magnetic fields of two wires react upon each other. This reaction may take place between two neighboring wires in the same circuit through which a current is flowing, or it may occur between wires in two independent circuits, the action depending on the relative directions of the two magnetic fields.

193. The Magnetic Fields of Parallel Currents. — The magnetic field of a straight wire carrying a current was illustrated in Fig. 124. If, for convenience, you regard magnetic lines as being of **N**-polarity when their direction is toward you, and of **S**-polarity when their direction is away from you, then

when the direction of the whirls is kept in mind, the **N**- and **S**-polarity of a straight wire may be readily remembered. In the left-hand diagram of Fig. 165 the direction of the current, the direction of whirls and polarity of the wire are indicated. The wires pass through a piece of cardboard upon which, by the aid of iron filings, the graphical field is made. The current in the parallel wires flows in *opposite* directions, so that the two adjacent sides are of the same polarity, thus causing a force of repulsion to exist between them. The wires tend to move away from each other. The field is very condensed between the wires and elongated outside of them. Midway between the wires the lines of force are in the same direction and are perpendicular to the plane of the loop of wire. The repulsion between the wires may be demonstrated by the following experiment.

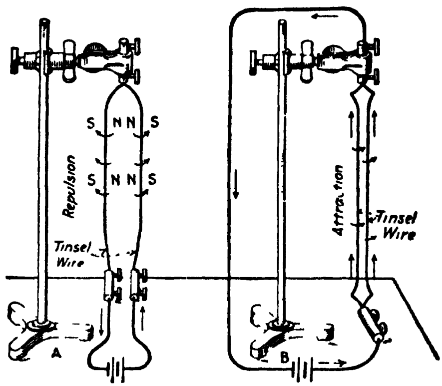


Fig. 166. -- Repulsion and Attraction between Suspended Tinsel Wires Carrying Currents.

A — Currents in opposite directions — repulsion
B — Currents in the same direction — attraction.

Experiment 73. — Support a wire connector and suspend therefrom two long, parallel pieces of tinsel wire arranged close to each other, and connect them to a source of current as shown at A of Fig. 166. When the circuit is closed the currents, being in opposite directions, repel each other and the wires move apart as depicted, according to the principle just stated.

In the right-hand diagram of Fig. 165, the currents in the parallel wires are in the same direction and the polarities of the adjacent wires unlike, so that attraction results according to the law for unlike polarities. This is noted in the filing diagram, where the field on the outside of the wires is very much condensed and elongated between these wires. There are also

continuous curves embracing both wires, due to the unison of some of the magnetic lines of both wires. The wires tend to be drawn together by the tension along these lines of force. This attraction is demonstrated in Experiment 74.

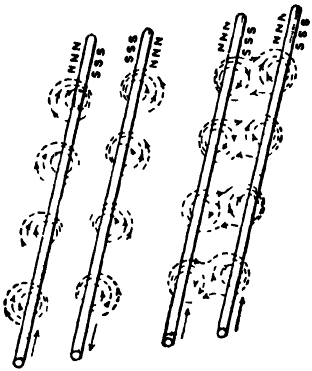


Fig 167. — Repulsion and Attraction between Parallel Currents.

Experiment 74.— Pass the current through the two parallel tinsel wires in B (Fig. 166) in the same direction. Although the wires were originally separated by some distance they move toward each other.

194. Laws of Parallel Currents. — 1. PARALLEL WIRES CARRYING CURRENTS FLOWING IN THE SAME DIRECTION ATTRACT EACH OTHER; BUT IF THE CURRENTS ARE IN OPPOSITE DIRECTIONS THEY REPEL EACH OTHER. See Fig. 167. This law is true for wires of independent circuits or for two parts of the same circuit.

2. THE FORCE BETWEEN TWO PARALLEL CURRENTS IS PROPORTIONAL TO THE PRODUCT OF THE CURRENT STRENGTHS AND TO THE LENGTH OF THE WIRES CONSIDERED, AND VARIES INVERSELY AS THE DISTANCE BETWEEN THEM.

The first law may be further demonstrated by the Ampere-frame coil shown in Fig. 168.

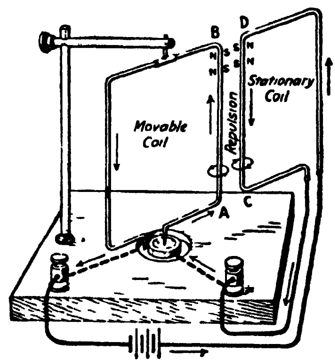


Fig. 168. — The Movable Coil (A B) may be Attracted or Repelled by the Stationary Coil (CD).

Experiment 75. — Connect the Ampere-frame coil and another coil in series to a source of current (Fig. 168). Trace the direction of current in each coil. Hold one side of the rectangular coil, CD, parallel and close to one side of the movable coil. AB. The wire AB is repelled and moves

away from CD when the currents are in opposite directions (Fig. 168). Invert the soil CD so that the current flows in the same direction through both, and the movable coil is attracted and will follow CD if it is carried around the axis of the coil AB

Experiment 76: Roget's Jumping Spiral. — A further demonstration of the first law employs a phosphor bronze spring, S, supported vertically by a stand (Fig. 169). The lower end dips into a cup of mercury, C. Current is passed through the spring and flows around each convolution in the same direction, hence the magnetic fields of all the convolutions attract each other, and the length of the spiral is shortened to such an extent that the lower end is pulled out of the mercury cup, thus breaking the circuit. Gravity now pulls the spring down again and the circuit is reëstablished, only to be broken by the same action. The spring thus vibrates continuously like the vibrator of an electric bell. An iron rod lowered through the center of the spiral, so that it does not touch the convolutions, greatly increases the action by increasing the magnetic effects of the whirls around each wire.

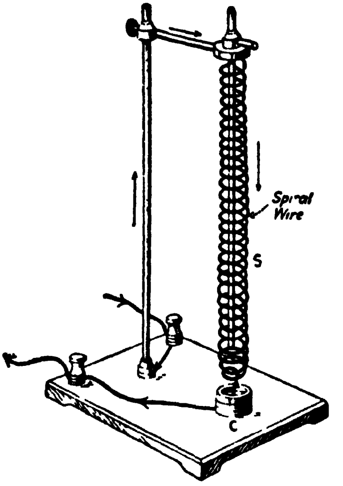


Fig. 169. — Roget's Jumping Spiral.

It illustrates the law of parallel currents flowing in the same direction.

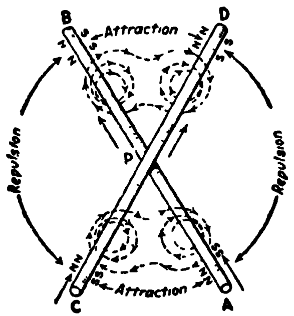


Fig. 170. — Attraction and Repulsion between Currents Flowing at an Angle to Each Other.

In any solenoid or electromagnet, the magnetic field, therefore, tends to bind the wires closer together, as in Roget's spiral, since the current is in the same direction through all the turns, and all the convolutions are parallel. The windings of electrical machines and apparatus must be designed to withstand the forces due to the currents in those coils, even under short-circuit conditions.

195. Currents in Conductors at an Angle with Each Other. — In Fig. 170 two insulated wires AB and CD make an angle with each other, and the currents flow from A and C toward P, and the portions AP and CP attract each other. This is indicated by the polarity of the wires and the direction of the whirls around them. Currents also flow away from P, toward B and D, and similar attraction takes place. Now consider the current and polarity in the part of the wire AP and PD. In AP the current flows toward P and in PD away from P, and repulsion exists as indicated. These facts are summarized by the following law:

TWO WIRES CROSSING EACH OTHER AT AN ANGLE ATTRACT EACH OTHER IF THE CURRENTS IN BOTH OF THEM FLOW EITHER TOWARD THE POINT OF CROSSING OR AWAY FROM IT; BUT THEY REPEL EACH OTHER WHEN THE CURRENT FLOWS TOWARD IT IN ONE WIRE AND AWAY FROM IT IN THE OTHER. The motion tends to make the wires not only parallel, but also coincident. This law is very important, and upon its principle are constructed electro-dynamometers and wattmeters (¶ 214, ¶ 223, etc.). This law can be demonstrated by the apparatus described in Experiment 77.

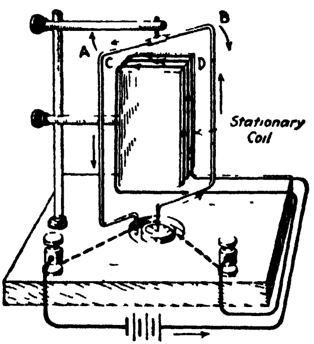


Fig. 171 — Angular Currents Tend to become Parallel and Flow in the Same Direction

Experiment 77. — Inside of the movable rectangular coil AB (Fig. 171) is clamped a fixed coil CD. The two coils may be connected in series or to two independent circuits The movable coil AB is turned so that its plane makes an angle with the plane of the coil CD. If the current be sent through the coils so that it flows along AB and CD either toward or away from their angle of intersection, the coil AB will move in the direction of the arrows till its plane coincides with that of CD, or till they are parallel, according to the foregoing law. If, now, the current through *either* but not both of them be reversed, the coil AB will move against the direction of the arrows and complete one-half revolution, till its plane coincides with CD, when B will be directly above C. This motion is in accordance with the latter half of the law which applies when the currents flow in one wire toward the point of crossing, and in the other wire away from it.

QUESTIONS

1. Two parallel wires are stretched from vertical supports, the measured distance between them being 2 inches. A current is sent through the wires, and the distance is now only $1\frac{3}{4}$ inches. How do you explain this?

2. If the current is reversed in both wires in Question 1, how will they now be affected?

3. Two wires cross each other at an angle of 60° and the current flows through them in opposite directions. Will they tend to move so as to increase or decrease the angle of crossing?

4. A vertical wire carrying a current rotates around the **S**-pole of a magnet in a direction against the hands of a clock as viewed from the **S**-pole end. Is the current flowing up or down the wire?

5. A copper disk is mounted between the poles of a horseshoe magnet and current is passed from its center to the circumference. Make a sketch indicating the direction in which the disk will rotate. How can you change the direction of rotation of the disk?

6. Current is passed downward through a vertical wire, and a bar magnet with its **N**-pole held uppermost is placed near to and parallel with the wire. Suppose the magnet to be flexible, like a piece of tinsel wire, what will occur? Make a sketch.

LESSON XVI

GALVANOMETERS

Principle of the Galvanometer — Detector Galvanometer — Sensibility of a Galvanometer — Shunts — Tangent Galvanometer — Tables XI and XII — Thomson Galvanometer — Reading Devices for Mirror-type Galvanometers — Astatic and Differential Galvanometers — D'Arsonval Galvanometer — The Ballistic Galvanometer — Ayrton Shunt — Questions and Problems.

196. Principle of the Galvanometer. — An instrument which measures a current by one of its effects is called a galvanometer. Galvanometers are used for detecting the presence of an electric current in any circuit, and for determining its direction and relative strength. Their construction is based on the principles: 1, that a magnetic needle is deflected when brought under the influence of a magnetic field produced in the neighborhood of a wire through which a current is flowing, or 2, that a coil suitably located between the poles of a permanent magnet will be deflected when a current traverses that coil. According to these principles of action, galvanometers may be divided into two classes: first, those in which the magnet or magnetized body is arranged to move and the coil held stationary, and second, those in which the magnet is stationary and the coil arranged to move. Each class is largely used in practice for laboratory and commercial purposes, and is constructed in a variety of forms. The method of supporting the moving system may be either by suspension, by poising it, or by delicate springs. The deflections may be noted either by a pointer attached to the system and moving over a graduated scale, or by a small mirror attached to the system. In the latter case, a ray of light falling upon the mirror is reflected upon a scale at some distance and greatly enlarges a small movement of the moving system. In another method the

image of the scale deflection is observed on the mirror by a telescope located at about the same distance as the scale (¶ 202).

A simple galvanometer consists essentially of a magnetic needle poised or suspended in the center of a coil of wire and provided with a circular scale, graduated in degrees, on which the deviation, or deflection, of the needle may be noted. When such an instrument is connected in a circuit the presence of the current therein is shown by the deflection of the needle. The direction of the current is shown by the side towards which the **N**-pole of the needle moves (¶ 167), and the strength of current is indicated by the amount of the deflection. The position that the needle takes up depends upon the relative magnitudes of the magnetic field due to the current and of the field due to the earth; it will point in the direction of the resultant of these magnetic fields. The earth's magnetism may be considered to be approximately constant at any particular place.

To obtain the maximum effect of the current's field, the galvanometer wire or coil, when no current is flowing, is arranged parallel to the magnetic needle when it is at rest, so that the plane of the coil passes through the axis of the needle and the magnetic meridian. *Such galvanometers are usually set up to conform to the above conditions before sending a current through them.* The greatest possible deflection of the needle is then 90 degrees, which places it at right angles to the coil. The value of the deflection is dependent upon the current flowing through the coil, but is not proportional to the current; that is, if one current produces twice the deflection of another current the former is not of double the strength. With the needle parallel to the coil, or at the zero scale position, a small current deflects it considerably, but as the angle the needle makes with the coil increases, a much greater magnetic force is required. For example, it requires a greater current to deflect the needle one degree from the 45-degree position than to deflect it one degree from the 15-degree position. The galvanometer coil may be wound with a great many turns of fine wire, in which case the instrument is said to be sensitive (that is, the needle is appreciably deflected by a very small

current), or it may be composed of a few turns of very heavy wire, in which case it is intended for use with large currents.

197. Detector Galvanometer. — A student's detector galvanometer is illustrated in Fig. 172, and the parts in Fig. 173. A circular glass-covered box contains the magnetic system inclosed in a rectangular coil wound with small wire. An aluminum pointer is fixed to an aluminum cap (Fig. 173) and the magnetic needle fastened to a glass jewel. The cap telescopes the jewel and the pointer is arranged at right angles to the needle. One-half of the dial is graduated in degrees and the other half in divisions corresponding to the tangents of the various angles (¶ 200). In adjusting this instrument for use, turn the box around till the pointer is directly over the zero mark on the scale; the pointer will then point east and west, and the magnetic needle at right angles to it will be in the magnetic meridian, as will also the coil of wire. The coil is wound with No. 30 B. & S. magnet wire, and has a resistance of about 30 ohms. The instrument is quite sensitive; a current of about 0.00001 ampere will deflect the needle 1 degree from its position of rest.

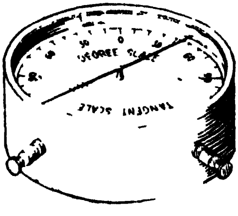


Fig 172. Student's Detector Galvanometer.

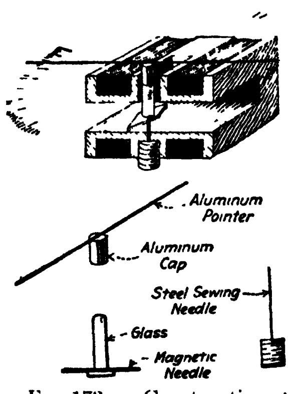


Fig. 173. — Construction of Student's Detector Galvanometer.

In measuring the resistance of the insulation around a piece of wire (Fig. 174), a current is passed from a sheet of tinfoil, wrapped around the insulated wire, through the cotton insulation to the wire itself. The value of this current is to be noted on the galvanometer in the circuit. The current that flows through this insulation will be very small, so that the galvanometer must be extremely sensitive to record such a minute current. For this

purpose a galvanometer of the type illustrated in Fig. 172 should have a coil small in diameter and wound with many turns of very fine wire, and the needle must be delicately pivoted to eliminate as much friction as possible.

On the other hand, suppose it is desired to indicate the current flowing through a number of incandescent lamps. If the foregoing galvanometer is connected in series with the lamps, its resistance would be so high that the lamps would not light, or the coil might be destroyed due to an excessive current passing through it. A galvanometer having a coil of large diameter and of few turns, and consequently of very low resistance, is suitable for this case. The total magnetizing force deflecting the needle may be the same as before, but is now produced by a large current circulating around a few turns, instead of a small current around thousands of turns (¶ 182).

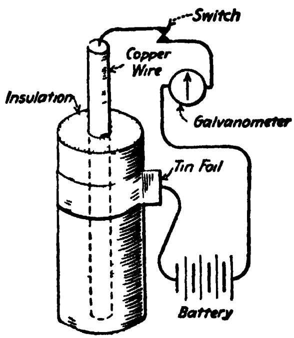


Fig 174 Measuring Insulation Resistance

Galvanometers of high resistance are used to measure electrical pressure and, when properly standardized, their scales are graduated to read directly in volts; the instrument then becomes a *voltmeter* (¶ 216). The standardization consists in experimentally determining the position of the needle, when the coil is subjected to different known pressures, and marking these values on the scale; the process is called *calibration.* It is still the current that deflects the needle but its strength is dependent upon the pressure. Galvanometers of very low resistance may have their scales calibrated to read directly in amperes, and thus become ampere-meters or *ammeters* (¶ 207).

198. Sensibility of a Galvanometer. — The sensitiveness of a galvanometer may be expressed by the amount of current required to produce a given deflection. The sensibility may also be indicated by the resistance which is placed in the galvanometer circuit so that one volt shall produce a certain deflection. For example, a galvanometer with a "sensibility of

2 megohms," means one in which the movable system will be deflected one division of the scale when it is connected in series with 2 megohms under a potential difference of 1 volt applied to the circuit.

The sensibility of a galvanometer depends upon the number of times the current circulates around the coil, the distance of the needle from the coil, the weight of the needle, and the amount of friction produced by its movement. The needle is usually quite small, and often a compound one. In very sensitive galvanometers of the moving-coil type the coils are wound with thousands of turns of very fine wire and the permanent magnets are strongly magnetized.

199. Shunts. — If the current passing through the galvanometer (G, Fig. 175) is too large, only a fraction of the total current should be passed through the galvanometer, the remainder passing through the wire S, connected across the galvanometer terminals. The wire S forms a "by-path" for the current, and is called a *shunt*, and the galvanometer is said to be *shunted*. If the resistance of the galvanometer is 1 ohm and that of the shunt 1 ohm, then as much current will flow through the shunt as through the galvanometer. If the resistance of the galvanometer is 2 ohms and that of the shunt 1 ohm, then twice as much current will flow through the shunt as through the galvanometer; that is, the galvanometer reading must be multiplied by 3 to obtain the total current flowing from the battery. The value 3 is called the *multiplying power of the shunt;* it is the amount by which the shunt multiplies the range of the galvanometer. Any galvanometer (ammeter or voltmeter) may have its range of indication increased by shunting it.

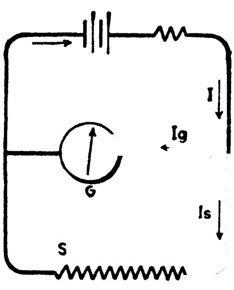


Fig. 175. — Shunted Galvanometer.

Let G = galvanometer resistance,
S = shunt resistance,
I = total current in the joint circuit,
Ig = current in the galvanometer circuit,
Is = current in the shunt.

Then the voltage across the galvanometer is the product of its resistance and current, or is $G \times Ig$; and similarly the voltage across the shunt is $S \times Is$. Since these voltages are equal for resistances connected in parallel, it follows that

$$G \times Ig = S \times Is$$

But $Is = I - Ig$, therefore,

$$G \times Ig = S \times (I - Ig) = S \times I - S \times Ig,$$

or, by adding $S \times Ig$ to both sides of the equation, its value is unaltered and

$$G \times Ig + S \times Ig = S \times I,$$

or

$$(G + S)Ig = S \times I.$$

The multiplying power of a shunt is the ratio of the total current, I, flowing in the circuit to that part of it, Ig, which flows through the galvanometer. This ratio from the last equation is

$$\text{multiplying power} = \frac{I}{Ig} = \frac{G + S}{S} = \frac{G}{S} + 1.$$

1. To find the multiplying power of a shunted galvanometer:

Divide the galvanometer resistance by the resistance of the shunt and add one to the quotient.

$$\text{Multiplying power of a shunt} \quad n = \frac{G}{S} + 1 \quad . \quad . \quad . \quad . \quad . \quad \textbf{(76).}$$

Problem 89. — Find the number by which the readings on a Weston voltmeter must be multiplied (or the multiplying power of the shunted galvanometer) in Fig. 176, when the resistance of the voltmeter (galvanometer) is 5000 ohms, and the resistance of a shunt placed across its terminals is 500 ohms.

By Formula (76)

$$n = \frac{G}{S} + 1 = \frac{5000}{500} + 1 = 10 + 1 = 11.$$

The readings are to be multiplied by 11 to obtain the true value of the total current flowing.

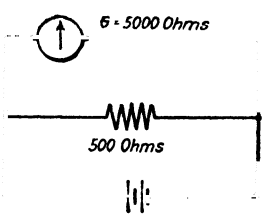


Fig. 176 — Current through a Shunted Galvanometer.

2. To find the current, Ig, flowing through a

SHUNTED GALVANOMETER WHEN THE TOTAL CURRENT, I, FLOWING THROUGH THE CIRCUIT IS KNOWN:

Divide the total current by the ratio of the galvanometer resistance to the shunt resistance, plus one.

$$Ig = \frac{I}{\frac{G}{S} + 1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (77).$$

Problem 90. — If 0.3 ampere flows from the battery in Fig. 176, when the galvanometer resistance is 5000 ohms and that of the shunt is 500 ohms, what current will flow through the galvanometer?

By Formula (77)

$$Ig = \frac{I}{\frac{G}{S} + 1} = \frac{0.3}{\frac{5000}{500} + 1} = \frac{0.3}{11} = 0.027 \text{ ampere},$$

3. TO FIND THE VALUE OF SHUNT RESISTANCE TO GIVE A CERTAIN MULTIPLYING POWER:

Divide the galvanometer resistance by the multiplying power desired, minus one.

Then,

$$S = \frac{G}{n - 1} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (78).$$

Problem 91. — What must be the resistance of a shunt to give a multiplying power of 100, when used with a galvanometer of 5000 ohms resistance?

By Formula (78)

$$S = \frac{G}{n - 1} = \frac{5000}{100 - 1} = \frac{5000}{99} = 50.5 \text{ ohms}.$$

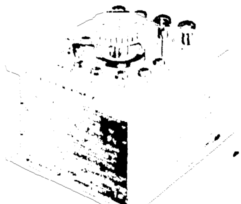


Fig. 177. — Shunt Box.

Shunt boxes for galvanometers have several coils whose resistances are calculated to give such ratios of n as 10, 100 and 1000. These coils may be arranged as a plug box, similar to Fig. 67; by withdrawing the plugs any particular shunt can be quickly connected to the galvanometer. The multiplying power is stamped on the box to correspond with each plug. This shunt box can only be used with the galvanometer (ammeter or volt-

meter), for which it was calculated. Another form of shunt box, called an Ayrton shunt (¶ 206) may be used with any galvanometer; it is illustrated in Fig. 177.

200. Tangent Galvanometer. — The *tangent galvanometer* consists of a circular coil of one or more turns of large diameter with a short magnetic needle poised at its center. It is called a tangent galvanometer because a particular function of each angle of the needle's deflection, called a *tangent*, is directly proportional to the current flowing through the instrument. There is, therefore, a direct law between the current and deflection when the instrument is properly constructed. The magnetic needle should be very small as compared with the diameter of the coil (for example, needle 0.75 inch long, diameter of coil 8 inches) so that the poles of the needle will be near the center of the coil where the magnetic field is practically uniform. The axis of the needle is parallel to the coil when no current is flowing, both being, therefore, in the magnetic meridian.

Instead of measuring an angle in degrees of an arc, it may be reckoned by some function of the angle. In Fig. 178 the position of the galvanometer needle when pointing to zero on the circular scale is represented by the line AB. Draw an indefinite line AF, perpendicular to AB, and tangent to the circle at point A. Suppose the needle is now deflected by the current to a point along the line BC, making the angle ABC of a certain number of degrees. The line AC is proportional to the tangent of the angle ABC. The value of this tangent increases as the angle opens out or increases; thus, if another current deflects the needle along the line BD, making the angle ABD of so many more degrees, the tangent of this angle is represented in value by the length of the line AD. When AD is equal to AB the value of the tangent, which is fully defined as the ratio of AD to AB, is unity, and the angle ABC is 45 degrees. When the needle is deflected at right angles, or 90 degrees, the radius prolonged will not intersect the tangent line, or the tangent of 90 degrees is infinity. The values of the tangents vary from 0 to infinity. The value of the tangent for each degree of angle is given in the following table. For example, the tangent of 60 degrees is 1.7321, which means that the length of the line AD is 1.7321 times as great as the radius AB.

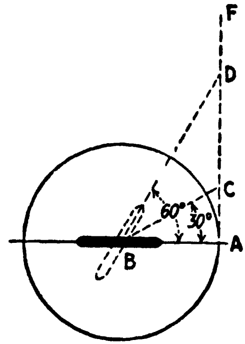


Fig. 178. — The Tangent of an Angle.

Table XI. Natural Tangents

Angle	Tan	Angle	Tan	Angle	Tan	Angle	Tan	Angle	Tan
0°	.0000	18°	.3249	36°	.7265	54°	1.3764	72°	3.0777
1	.0175	19	.3443	37	.7536	55	1.4281	73	3.2709
2	.0349	20	.3640	38	.7813	56	1.4826	74	3.4874
3	.0524	21	.3839	39	.8098	57	1.5399	75	3.7321
4	.0699	22	.4040	40	.8391	58	1.6003	76	4.0108
5	.0875	23	.4245	41	.8693	59	1.6643	77	4.3315
6	.1051	24	.4452	42	.9004	60	1.7321	78	4.7046
7	.1228	25	.4663	43	.9325	61	1.8040	79	5.1446
8	.1405	26	.4877	44	.9657	62	1.8807	80	5.6713
9	.1584	27	.5095	45	1.0000	63	1.9626	81	6.3138
10	.1763	28	.5317	46	1.0355	64	2.0503	82	7.1154
11	.1944	29	.5543	47	1.0724	65	2.1445	83	8.1443
12	.2126	30	.5774	48	1.1106	66	2.2460	84	9.514
13	.2309	31	.6009	49	1.1504	67	2.3559	85	11.430
14	.2493	32	.6249	50	1.1918	68	2.4751	86	14.301
15	.2679	33	.6494	51	1.2349	69	2.6051	87	19.081
16	.2867	34	.6745	52	1.2799	70	2.7475	88	28.636
17	.3057	35	.7002	53	1.3270	71	2.9042	89	57.290

When it is desired to compare the relative strength of two currents, each is passed through the tangent galvanometer, properly set up, and the corresponding deflections noted. The first current will bear the same relation to the second current that the tangent of the first angle bears to that of the second angle. The values of the tangents are taken from the table. Calling I and I_1 the two currents to be compared and d and d_1 the deflections in degrees produced by these currents respectively, then:

I is to I_1 as tan of d is to tan of d_1,

or
$$I = \frac{I_1 \times \tan d}{\tan d_1} \quad \ldots\ldots\ldots\ldots \quad (79).$$

Problem 92. — A tangent galvanometer is deflected 17° when inserted in series with a solenoid and a Daniell cell. When a Grenet cell is substituted the deflection is 31°. What is the relative strength of current through the solenoid when the Grenet cell is used?

Here $d = 17°$, $\tan d = 0.3$; and $d_1 = 31°$, $\tan d_1 = 0.6$.

By Formula (79)

$$I = \frac{I_1 \times \tan d}{\tan d_1} = \frac{I_1 \times 0.3}{0.6}, \quad \text{or} \quad I = \frac{1}{2} I_1,$$

or the current delivered by the Grenet cell was twice as strong as the current from the Daniell cell.

Problem 93. — If one ampere deflects the needle of a tangent galvanometer 5° how many amperes will deflect it 50°?

In this case I = 1 ampere, d = 5°, tan d = 0.0875, d_1 = 50°, tan d_1 = 1.1918.

From Formula (79)

$$I_1 = \frac{I \times \tan d_1}{\tan d} = \frac{1 \times 1.1918}{0.0875} = 13.6 \text{ amperes.}$$

If a tangent galvanometer is constructed or adjusted so that one ampere deflects the needle 45°, since the tangent of 45° equals one, the value of the tangent of any other angle of deflection will represent the value of the current in amperes passing through the instrument.

For many laboratory measurements the combination tangent galvanometer, illustrated in Fig. 179, may be used. It consists of the detector galvanometer (described in ¶ 197) placed in position in the tangent coil frame, 8 inches in diameter, constructed of hard wood and mounted on a suitable base. When placed in position its needle is in the center of the coils on the frame, and the three brass leveling screws underneath the base are used to level the instrument so that the glass jewel rides freely on its pivot. There are four coils of No. 18 B. & S. wire on the frame, each with 2 turns per coil. The terminals of each coil are connected to binding posts; the figure shows the binding posts of two coils, the other four posts being on the opposite side. Fig. 180 shows a diagram of the method of winding, also the method of connecting the four coils in series. The coils are all wound in the same direction, B representing the beginning of a coil and E its ending. The advantage of the separate coils is that they can be connected in series-parallel or multiple-series; so that the magnetic effect upon the needle can be altered by varying the number of turns on the galvanometer. Deflections may be read from the degree scale of the instrument and the tangents obtained from the table, or the deflections on the tangent scale may be read directly since they are proportional to the current. The resistance of the four coils connected in series is 0.165 ohm, and a current of 0.25 ampere through them will deflect the needle 45°.

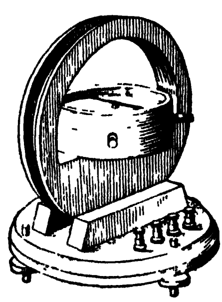


Fig. 179. — Student's Tangent Gavanometer.

Experiment 78. — Send a current of known strength, say 0.5 ampere, around one coil of the galvanometer, and note the deflection on the tangent scale. The current flows twice around the needle, since there are two turns per coil. Pass the same strength of current through two coils in series. The current flows four times around the needle and it is deflected to a value on the tangent scale double that of the first case. If three coils are used in series the tangent scale value is tripled. Note also the degree scale deflections, and compare the value of the tangents taken from the table for each deflection.

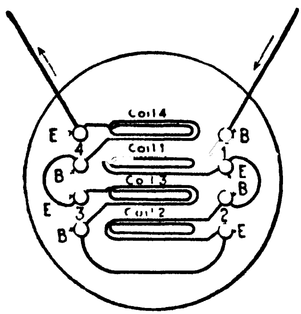


Fig. 180. -- Winding Diagram of Tangent Galvanometer.

The four coils are shown connected in series.

The sensibility (¶ 198) of the galvanometer is, therefore, directly proportional to the number of convolutions of wire on the coil. If the coil had been increased to twice the diameter and the same current had been passed twice around it, the tangent of the angle of deflection would have been just one-half that produced by the same current flowing twice around the smaller coil; therefore, the sensibility is also inversely proportional to the diameter of the coil, that is, decreasing the diameter increases the sensibility, and vice versa.

The value of any current sent through the tangent galvanometer may be calculated directly in amperes from the following formula, when the dimensions of the instrument are known. The needle is supposed to move in a horizontal plane and not controlled by any force other than the earth's magnetism.

Let I = current in amperes,
r = *radius* of coil in inches,
N = number of turns in the coil,
d = angle of deflection of the needle in degrees,
H = a constant from the table on the next page, which takes care of the horizontal force of the earth's magnetism at the place where the galvanometer is used.

Then

$$I = \frac{H \times r}{N} \times \tan d. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (80).$$

Table XII. Tangent Galvanometer Constants. — Values of H

Boston,	0.699	New Haven,	0.731
Chicago,	0.759	Philadelphia,	0.783
Denver,	0.919	Portland, Me.,	0.674
Jacksonville,	1.094	San Francisco,	1.021
London,	0.745	St. Louis,	0.871
Minneapolis,	0.681	Washington,	0.810
New York,	0.744		

Since the tangent of the angle of deflection in Formula (80) is always to be multiplied by a constant number, $\frac{H \times r}{N}$, for a particular instrument and place, this number is called the *constant of the galvanometer.*

Let K = constant of the galvanometer = $\frac{H \times r}{N}$, then from Equation (80),

$$I = K \times \tan d \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (81).$$

Problem 94. — A Daniell cell is connected to 4 coils of the student's tangent galvanometer connected in series, and the needle is deflected 30 degrees. The diameter of the coil is 8 inches, and with 4 coils in series having 2 turns per coil, the total turns are 8. What current is flowing through the instrument if it is located in New York?

For New York H = 0.744; also r = 4 inches, N = 8 turns, tan 30° = 0.5774.

By Formula (80)

$$I = \frac{H \times r}{N} \times \tan d = \frac{0.744 \times 4}{8} \times 0.5774 = 0.214 \text{ ampere}$$

Problem 95. — What is the constant of the galvanometer in Problem 94

$$K = \frac{H \times r}{N} = \frac{0.744 \times 4}{8} = 0.372.$$

201. Thomson Galvanometer. — In the Thomson galvanometer (Fig. 181) great sensibility has been attained by bringing the coil as close to the needle as possible and winding it with many turns of very fine wire.

On the back of a small mirror, about ½ inch in diameter, are fastened by shellac, a number of magnetic needles with their N-poles in one direction. The mirror is suspended in the center of the coil, so that the needles hang horizontally, by a fine cocoon silk fiber which extends the entire length of the vertical brass tube shown in Fig. 181. The cylindrical box housing

the coil is mounted on a tripod, provided with leveling screws, and can be rotated on its vertical axis The curved controlling magnet, arranged on the vertical tube, can be revolved, or raised and lowered, with regard to the magnetic needle. The instrument is most sensitive when placed with its coil in the magnetic meridian, with the controlling magnet elevated to such a position that its force upon the suspended needles partly neutralizes the action of the earth's attractive force upon them.

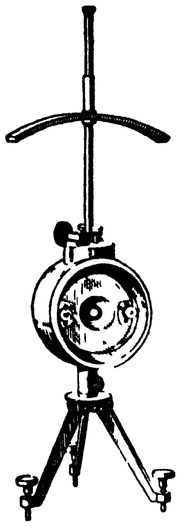


Fig 181 — Thomson Mirror-reflecting Galvanometer (Single-coil Type.)

202. Reading Devices for Mirror-type Galvanometers. — To use the Thomson galvanometer (Fig. 181) or any other mirror-reflecting galvanometer, the room is darkened and a ray of light is projected upon the galvanometer mirror from a light source placed about two or three feet distant from the galvanometer. A graduated scale is fixed just above the source of light and the suspended system of the galvanometer is adjusted so that the reflected beam of light strikes the scale. Fig. 182 shows a Leeds & Northrup reading device consisting of a galvanometer scale and lamp. The zero position of the scale is located at the center so that the beam may swing to the right or left of zero. The spot of light is brought to the zero position by the controlling magnet, or by twisting the fiber suspension by means of the knurled knob at the top of the

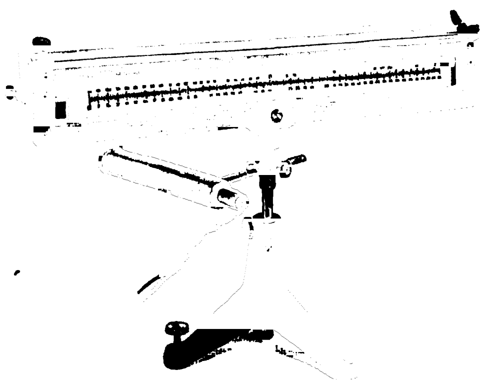


Fig. 182. — Reading Device for Use with Mirror-type Galvanometers.

tube. The angle between the original and reflected beams of light will be twice the angle of deflection of the mirror; the deflections of the spot of light on the scale are practically proportional to the strength of currents through the instrument.

Another reading device, shown in Fig. 183, does not require a dark room, as the scale readings are reflected in the mirror and their value observed by means of the telescope.

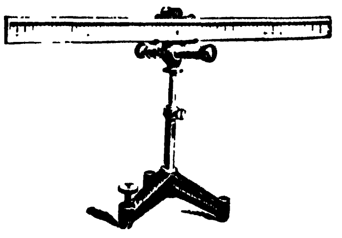


Fig. 183. Telescope and Scale for Use with Mirror-type Galvanometers.

203. Astatic and Differential Galvanometers.—If two needles of equal magnetic strength are fastened, one above the other, to a vertical rod with like poles in opposite directions, thus forming an *astatic needle*, and the rod is suspended, the earth's field has almost no directive force on the magnetic system. This principle is used in increasing the sensibility of galvanometers.

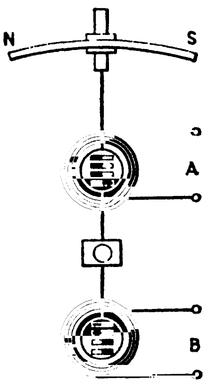


Fig 184.—Mirror-reflecting Astatic Galvanometer.

The Thomson mirror-reflecting astatic galvanometer has a coil surrounding each of the needles forming the astatic needle, and these coils are connected so that the direction of current in both coils will tend to turn the system in the same direction.

In this type of instrument the magnetic needles are compound and fastened to a small mica disk; the construction of the movable system in this instrument is shown in Fig. 184. Two mica disks, to which the needles are secured, are joined by a stiff wire, the mirror being mounted on a mica vane and secured to this wire. The mica vane assists in damping, by increasing the air resistance to turning, thus preventing the system from swinging back and forth for a long time after each deflection, and renders the instrument *dead-beat*. The whole system is suspended by a cocoon fiber attached to the upper end of a vertical brass tube, mounted on top of the case containing the coils A and B. A controlling magnet N S, is also provided to bring the needle system to zero and to alter its sensibility. The coils A and B may be used separately for comparing two

different current strengths at the same time by having the direction of the current in the coils such as to tend to turn the moving system in opposite directions. When so used the instrument is called a *differential galvanometer*.

204. D'Arsonval Galvanometer. — The D'Arsonval galvanometer (Fig. 185) is an example of that class in which the magnet is stationary and the movable system consists of a small coil of wire instead of a magnetic needle. The coil of wire is wound upon a rectangular bobbin and suspended by a fine silver or phosphor bronze wire between the poles of a laminated horseshoe magnet, so that the horizontal axis of the coil is at right angles to the magnetic lines of force between the poles of the magnet. When a current is led to and from the coil by means of the suspension wires above and below it, the coil becomes a magnetic body, and tends to turn so that its lines of force will be in the same direction as those of the permanent magnet. The coil will move to the right or left, depending upon the direction of current through it. This tendency to rotate is opposed by the torsion of the suspension wire, and the motion continues until the turning effort (or torque) due to the current is equal to the opposing torque of the suspension.

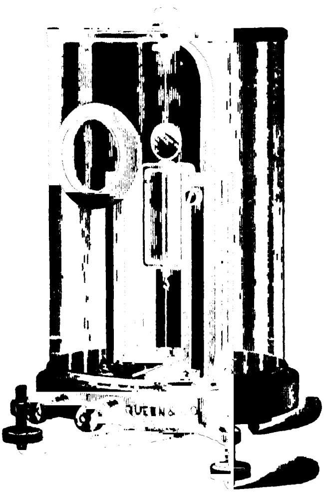


Fig. 185. D'Arsonval Galvanometer.

A stationary piece of soft iron is arranged in the center of the coil and supported from the back, its purpose being to increase the strength of the magnetic field in which the coil moves by reducing the reluctance of the flux path. By properly shaping the pole pieces the magnetic field may be modified so that the *deflection of the coil will be directly proportional to the current traversing it.*

If the coil is wound upon a non-magnetic metallic frame, the instrument will be very dead-beat, for the instant the coil moves induced currents are set up in the coil frame, and these are in such a direction as to tend to stop its movement (¶ 263). A mirror is attached to the coil so that the instrument may be used with a telescope and scale (Fig. 183) or with a lamp and scale (Fig. 182).

To ascertain the torque on the moving system of a D'Arsonval galvanometer, let

I = current in amperes,
A = area included by the coil,
N = number of turns in the coil,
H = field intensity in the air gap where coil is located.

Then,

$$\text{torque} = A \times N \times I \times H$$

This equation shows that a sensitive instrument should have a strong magnetic field, and that the coil should have many turns of wire wound on a relatively large bobbin.

These principles are utilized in the high-sensibility D'Arsonval galvanometer shown in Fig. 186, in which the magnets are of large section in order to secure an intense field. The coil is suspended between the specially shaped pole pieces and has a resistance of about 500 ohms. One volt will produce a deflection of 1 mm. division at a scale distance of 1 meter (from mirror) through a resistance of 10,000 megohms.

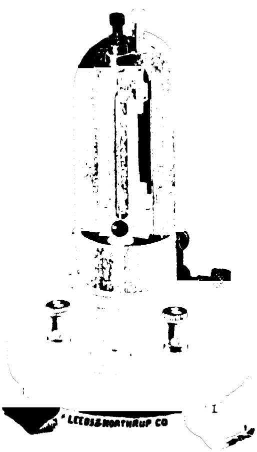


Fig. 186. — High Sensibility D'Arsonsal Galvanometer with Protecting Case Removed.

A portable form of D'Arsonval galvanometer that is quite sensitive and particularly well adapted for the measurement of very small currents, for measuring insulation resistance and for Wheatstone bridge resistance measurements (¶ 232) is shown in Fig. 187. In this particular form the moving coil, instead of being supported by a delicate suspension wire, is accurately fitted into jeweled bearings. The movement of the coil is

controlled by means of two springs which act against each other; this method is more certain in action than the torsion of a long suspension wire, and less liable to injury. This principle is used in the construction of the Weston instruments (¶ 212) for measuring direct currents.

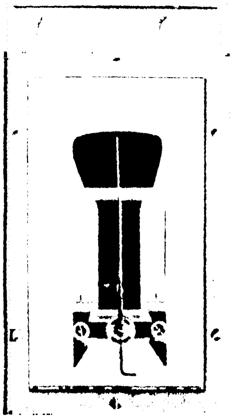


Fig 187 — D'Arsonval Galvanometer

Made by the Weston Electrical Instrument Co

The advantage of the D'Arsonval type of instrument over that of the Thomson form is, that it is not affected by the earth's or other external magnetic fields, so that it may be used in close proximity to dynamos.

205. The Ballistic Galvanometer. — A form of D'Arsonval galvanometer which is used for measuring momentary currents (as induction currents or condenser discharges, ¶ 342) is called a *ballistic galvanometer* (Fig. 188). Its coil is wide, is constructed to have considerable weight, and is arranged to have a small damping effect. If a momentary current be passed

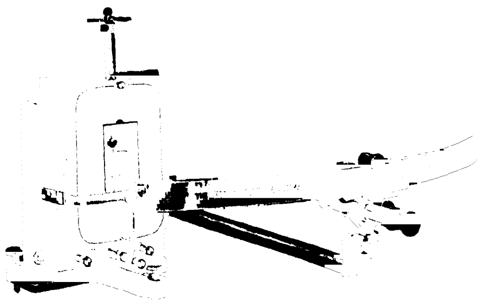


Fig. 188. - Ballistic Galvanometer with Attached Scale and Telescope.

Made by the Leeds & Northrup Co.

through its coils, the impulse given to the element does not cause appreciable movement of the magnetic system until the

current ceases, owing to the inertia of the heavy moving parts, the result being a slow swing of the system. The maximum deflection or "throw" is noted on the scale just at the point where the system ceases to move and begins to swing back to zero. This throw is a measure of the quantity of electricity sent through the coils. The instrument shown has a resistance of about 2000 ohms and will produce a deflection of 1 mm. on the scale by a quantity of electricity of about 0.003 microcoulomb, the time of the ballistic throw from the position of rest to its maximum deflection being nearly 5 seconds.

206. Ayrton Shunt.—A shunt which is extensively used with galvanometers is arranged as in Fig. 189; its external appearance is shown in Fig. 177. It may be used with galvanometers having widely different resistances. It will be observed that the galvanometer in Fig. 189 is shunted by the entire shunt composed of four resistances a, b, c and d in series, when the switch arm is placed on the contact marked 1. Let the current that flows through the galvanometer for this position of the switch arm be I. The resistances a, b, c and d of the shunt are so calculated that when the arm is on contact 0.1 the galvanometer current is 0.1 I, when on contact 0.01 the galvanometer current is 0.01 I, and when on contact 0.001 the galvanometer current is 0.001 I. Note in Fig. 189, when the contact arm is moved from right to left, that resistance is cut out of the shunt and added to the galvanometer circuit. Consideration will show that if R be the entire resistance of the shunt then

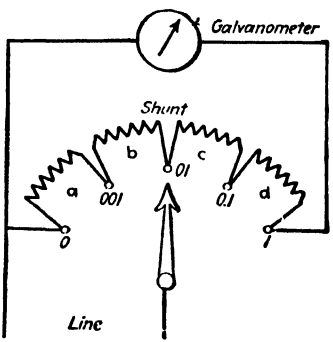


Fig. 189. Diagram of Ayrton Shunt.

$$d = \frac{9}{10} R, \quad c = \frac{99}{100} R - d, \text{ and } b = \frac{999}{1000} R - c - d.$$

Thus, if R = 3000 ohms, then d = 2700 ohms, c = 270 ohms, b = 27 ohms and a = 3 ohms.

QUESTIONS

1. State how you would proceed to measure the current flowing through a number of incandescent lamps with a high-resistance galvanometer.

2. The sensibility of a certain galvanometer is four megohms. What is meant by this statement?

3. Give a general classification of galvanometers according to the principles employed in their construction.

4. Upon what factors does the sensibility of a tangent galvanometer depend?

5. Why is it necessary to construct such very sensitive instruments?

6. What advantage does a dead-beat galvanometer possess over one that is not so constructed?

7. Explain what is meant by a differential and a ballistic galvanometer.

8. How would you arrange a low-resistance sensitive galvanometer so that it could be used for measuring electrical pressure?

9. Explain now a galvanometer can measure electrical pressure, since the deflection of its magnetic system is dependent upon the strength of the current actuating it

10. What are the advantages of a D'Arsonval galvanometer over the tangent type?

11. How would you construct a sensitive D'Arsonval galvanometer?

12. Make a sketch of a double coil astatic galvanometer with the coils joined in parallel Show the direction of current around the needle, and indicate the direction in which the system will be deflected by the current

PROBLEMS

1. An unknown current deflects the needle of a tangent galvanometer 27 degrees; the galvanometer constant is 0.65 What is the strength of current flowing through the instrument? *Ans.* 0 33 ampere.

2. A current of 4.6 amperes is sent through the galvanometer of Problem 1. What will be the corresponding deflection of the needle? *Ans.* 82°.

3. The resistance of a galvanometer shunt is 0.2 ohm and that of the instrument with its leads 24 ohms. What pressure is required to send 10 amperes through the joint resistance of the galvanometer and its shunt in parallel? *Ans.* 1.9 volts.

4. How much of the current flows through the galvanometer in Problem 3? *Ans.* 0.082 ampere.

5. What is the multiplying power of the above shunt? *Ans.* 121.

6. A four-coil Ayrton shunt having the ratios depicted in Fig. 189 has a total resistance of 10,000 ohms. Calculate the resistance of each coil. *Ans.* 10, 90, 900 and 9000 ohms.

LESSON XVII

AMMETERS AND VOLTMETERS

Ammeters or Ampere-Meters — Solenoidal Ammeter, Gravity Type — Thomson Inclined-Coil Ammeter — Weston A.C. Ammeters — Hot-Wire Ammeters — Weston D. C. Ammeters — Ammeter Shunts — Portable Dynamometer Ammeter; Electrodynamometer — Connecting Ammeters in Circuit — Measurement of E. M. F. and Potential Difference — Construction of Voltmeters — Weston Direct-Current Voltmeters — Multipliers — Connecting Voltmeters — Potentiometer — Questions

207. Ammeters or Ampere-Meters. — An *ammeter*, which is the commercial name for ampere-meter, is a galvanometer so constructed that the deflection of the needle indicates directly the strength of current in amperes flowing in a circuit in which it may be inserted. A great variety of measuring instruments have been developed, based upon the principles given in ¶¶ 20 and 192. The instruments in general use are classified according to their construction into two types: (1) fixed coil and moving iron type, and (2) fixed permanent magnet and movable coil type.

Instruments of the moving iron type may be used to measure either direct or alternating current, but those of the permanent magnet and movable coil type can only be used to measure direct current.

A good ammeter should have a *very low resistance*, so that very little of the energy of the circuit in which it is inserted will be absorbed by it; the needle should be *dead-beat*, and so sensitive as to respond to minute variations of current; the scale divisions should not be cramped at the scale ends, but even throughout; and the accuracy of the instrument should not be impaired when in close proximity to powerful magnetic fields, as surround switchboard conductors or dynamos. Ammeters are divided according to their use, into two classes: (1) a

portable type, generally of a high class of construction and accuracy, used for measurements of precision, and (2) the *switchboard type*, in the construction of which such refinement of precision is not required. In some meters of both types the *whole current* passes through the ammeter, while in others the ammeter is *shunted* (¶ 199). *Milliammeters* are ammeters in which the scale is graduated to read directly in thousandths of an ampere.

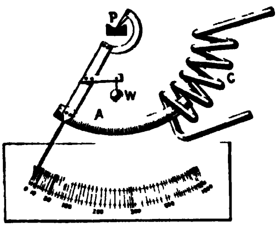


Fig. 190 — Solenoid Gravity Ammeter.

208. Solenoidal Ammeter, Gravity Type. — In this simple type of ammeter, the magnetizing current causes the attraction of a piece of suspended iron. The current passes around a helix of *heavy wire*, which is bent in the arc of a circle, C in Fig. 190. A soft iron core A, bent to the same arc, is suspended at P so that one end is free to be sucked up into the helix, C, by the field of the magnetizing current. A pointer attached to the movable iron core moves over the scale, which is calibrated by sending known currents through the helix. The control is effected by means of the weight W, called a gravity control. Suppose that 10 amperes are sent through the helix, and the core moves to such a position as to accommodate through itself the greatest number of the magnetic lines of the helix, then the limit of the scale is attained and the range of the instrument is from 0 to 10 amperes. The objection to this type of instrument is that the movement of the core is much greater at some positions than at others for the same increment of current, giving a scale of unequal divisions, and generally cramped at each end. The instrument is not



Fig. 191. — Thomson Inclined-coil Ammeter.

dead-beat, is readily affected by outside magnetic fields, and can only be used in a vertical position. This type of instrument may be calibrated for use on alternating-current circuits as well as for direct-current circuits.

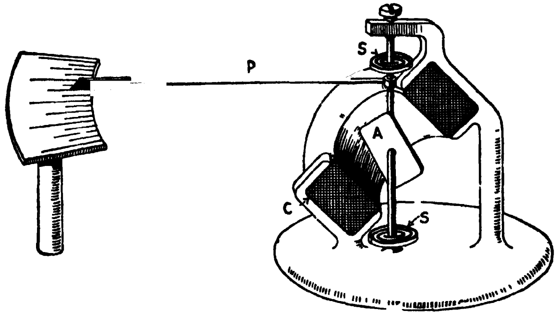


Fig. 192. — Construction of Inclined-coil Ammeter

209. Thomson Inclined-Coil Ammeter. — The Thomson ammeter, constructed in the portable and switchboard patterns, is another form of the solenoidal type instrument, having a fixed coil and movable magnetic vane. The movable element consists of a small piece of iron so placed that it will gradually move to a position to accommodate through itself the greatest number of lines of force of the magnetizing coil. A view of the portable type, with cover removed, is shown in Fig. 191, and a sectional view in Fig. 192. A circular coil of wire, C, is mounted with its axis inclined to the horizontal. Through the center of the coil is passed a vertical shaft mounted between jewel centers and carrying a pointer at its upper end. A small iron vane, A, is suitably attached to the shaft at an angle,



Fig. 193. — Interior View of Weston A. C. Ammeter.

and the movable system is controlled by the two flat springs S, S. When current is passed through the coil the vane tends to turn against the action of the springs, so as to become parallel to the lines of force passing downwardly through the center of the coil. The turning of the shaft causes the pointer P to sweep over the scale. The coils for large sizes of instruments are generally wound with a few turns of flat insulated copper ribbon having a very low resistance. These meters are adapted for use with alternating or direct currents.

210. Weston A. C. Ammeters. — The instruments made by the Weston Electrical Instrument Co. primarily for measuring alternating currents and alternating E. M. F.'s are also of the "moving iron" type but are so constructed that many of the defects of the other solenoidal types have been eliminated. The moving element consists of a small curved piece of iron fastened to a light pivoted shaft (Fig. 193). To this shaft is also fastened a truss form of pointer made of thin aluminum tubing, to which is attached a balance cross and a small vane. Near the movable element and concentric with it is a small curved tongue of soft iron, which is rigidly held by a suitable support. Surrounding this is a field coil, made up either of a large number of turns of fine wire when the instrument is to be used as a voltmeter, or else of one or more turns of heavy wire when designed as an ammeter. When a current is passed through the field coil, the movable element and the fixed tongue of iron become magnetized by induction; since both pieces of iron are within the field coil, their adjacent ends will have like polarities and consequently there will be repulsion between them. The only motion possible is

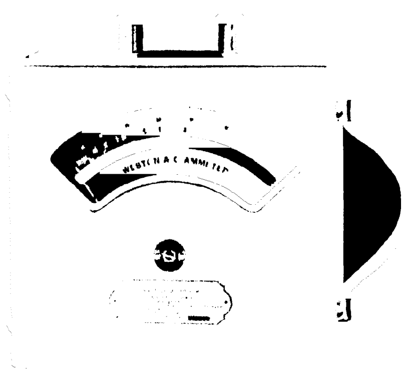


Fig. 194. — External View of Weston A. C. Ammeter.

the rotation of the movable element; this motion is opposed, and therefore controlled, by the action of a delicate spiral spring. The fixed tongue has a triangular shape so that the scale becomes more uniform. Damping of the movable system is caused by the vane which moves through confined air in the fan-shaped pocket, shown in Fig. 193 with its cover removed. An external view of this type of instrument is shown in Fig. 194.

211. Hot-Wire Ammeters. — The hot-wire type of ammeter utilizes the heating effect of the electric current for measuring current; the flow of current through a wire causes heating and a consequent expansion of the wire through which it passes. The expansion of the wire is taken up by a spring which causes a pointer to move across a graduated scale.

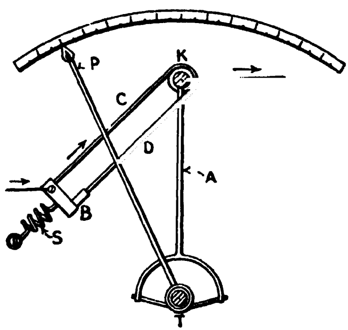


Fig. 195. — Hot-wire Ammeter.

Instruments of this type are not affected by magnetic fields and may be used to measure either direct or alternating currents, but there are certain objections to their use, namely: they are slow in action, require frequent resetting to zero and consume a greater amount of energy than other types. However, this type is particularly well adapted to measuring alternating currents of high frequency as used in wireless telegraphy, owing to the fact that the self-induction (¶ 266) of the wire is practically zero.

Fig. 195 shows the mechanism of a hot-wire ammeter. The wire CD passes around the pulley K and is held taut by spring S acting on the insulating plate B. The current to be measured flows only through the branch C of the wire, and consequently that branch lengthens. The slack is taken up by a slight rotation of the pulley K, which causes arm A (pivoted at K) to move. This arm has two prongs at its lower end between which a thread is stretched after looping itself around shaft T at the lower end of the pointer P. The slight expan-

sion of the wire is thus magnified by the mechanism so that a large scale reading is obtained.

212. Weston D. C. Ammeters. — The instruments, manufactured by the Weston Electrical Instrument Co., for measuring direct currents and electromotive forces, are in reality a portable form of D'Arsonval galvanometer, having a permanent magnet and a movable coil. When the instrument is designed as an ammeter the movable coil is shunted across a low resistance (¶ 213), if it is to be used as a voltmeter (¶ 217) a high resistance is inserted in series with the movable coil. This type of instrument is far superior to the "moving iron" type; it is extremely accurate, has a uniform scale, and is absolutely dead-beat. A permanent horseshoe magnet M is fitted with soft-iron pole pieces P, P (Fig. 196) between which a stationary cylinder of soft iron C is supported by a brass plate extending across the pole pieces. The iron cylinder is smaller in diameter than the bore of the pole pieces, so that the magnetic lines of force pass across this air gap, making a very strong and uniform magnetic field.

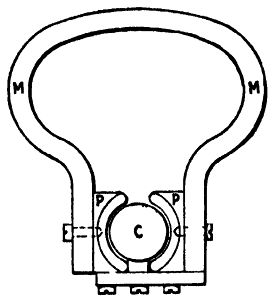


Fig. 196. — Magnetic Circuit of the Weston D.C. Instruments.

The movable coil (Fig. 197) consists essentially of a light rectangular coil of copper wire, usually wound upon an aluminum frame, pivoted in jewel bearings, and mounted to rotate in the annular space between the soft iron core and the specially formed pole pieces of the permanent magnet (Fig. 198). A light tubular pointer is rigidly attached to the coil and

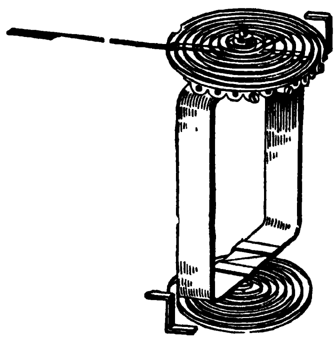


Fig. 197. — Movable Coil, Springs and Pointer of Weston D.C. Instruments.

moves over a graduated scale. The terminals of the coil are connected to the horizontal spiral springs, against which the coil acts when it tends to rotate, the springs serving also to conduct the current to and from the coil. When a current is sent through it, the coil tends to move through the magnetic field, to take up a position so that its lines of force will be in the same direction as those of the field. It will so

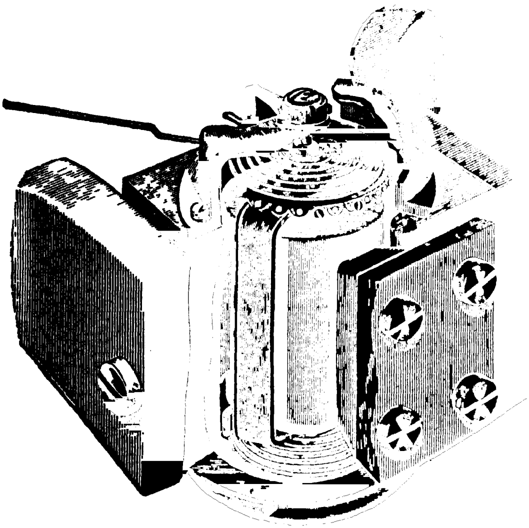


Fig. 198. — Method of Mounting Movable Coil in Weston Instruments.

move until the torsion of the springs is balanced by the force tending to move the coil, when the pointer will indicate the angle of deflection. The angle of deflection is nearly proportional to the current throughout the movement, which results in a very uniform scale. The movable coil is extremely light, the friction small, and hence the instrument is very sensitive to minute variations of current. The instrument is carefully balanced, so that it may be used in a horizontal or vertical position. An ammeter, however, should always be calibrated in the position in which it is to be used.

The aluminum frame on which the coil is wound has an electromotive force induced in it, when rotating in the magnetic field, which causes eddy currents (¶ 263) to flow around the frame in the opposite direction to the current in the coil. These momentary currents tend to stop the motion of the coil, and have the effect of preventing the needle from oscillating, thus bringing it to rest quickly at the proper position and making the instrument very dead-beat.

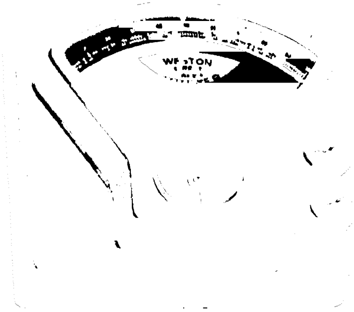


Fig. 199. – Weston Ammeter with Self-contained Shunt

A mirror is located just below the scale of the portable instruments. By looking down on the pointer so that it is directly over its reflection in the mirror, errors in reading the scale divisions due to *parallax*[1] are avoided. In D. C. instruments the post marked + is the one at which the current should enter the instrument so that the coil will be deflected in the right direction. A Weston portable Model 1 D. C. ammeter with self-contained shunt is shown in Fig. 199.

213. Ammeter Shunts. — As the Weston direct-current instruments are merely D'Arsonval galvanometers, they may be used either as ammeters or voltmeters according to the resistance of the movable coil, that is, whether the resistance is low or high. These instruments are really all *millivoltmeters* a few thousandths of a volt being sufficient to cause a full-scale deflection of the needle, and, as the wire on the movable coil is so fine that it can carry but a small fraction of an ampere, a *shunt* (¶ 199) must be placed across the movable coil in order to use this device to indicate larger currents. Only a small fraction of the main current will then flow through the moving coil, the remainder passing through the shunt.

The shunt is made of such a material or combination of materials, forming a special resistance alloy, that does not appre-

[1] The apparent angular displacement of an object when seen from two different points of view.

ciably change in resistance as its temperature changes. The shunt may be placed in the instrument, in a separate portable case (Fig. 200), or in the busbars on the back of a switchboard. Fig. 201 shows a shunt used with the switchboard type of instruments. The lead wires to the shunt, the instrument, and the shunt are all numbered to correspond, so that when used together the indications agree with the calibration. The shunt leads should never be shortened, because the decreased resistance in the shunt circuit would permit more current to flow through it, so that the indicated readings would be higher than the actual current flowing. One advantage of an external shunt in switchboard instruments for power stations is, that instead of running heavy copper cables to a distant ammeter, a shunt may be inserted in the cable circuit and the two small-sized shunt leads wired to the instrument, thus effecting an economy in copper and construction. The resistance of the instrument and its shunt is very low; little energy will, therefore, be lost when it remains continually in circuit.

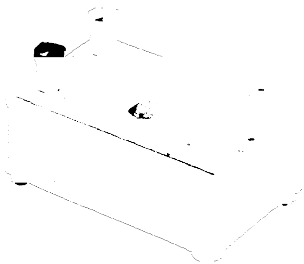


Fig. 200. — Portable Ammeter Shunt.

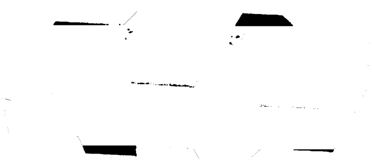


Fig. 201. — Separate Shunt for Switchboard Ammeters.

A number of shunts are sometimes furnished for a single portable instrument and mounted in a separate case called a shunt box, which is used for increasing the range or capacity of the instrument. For example, suppose the coil with a shunt of 0.004 ohm receives sufficient current to deflect the pointer entirely across the scale, and this deflection corresponds to 50 amperes in the main circuit. The difference in pressure between the shunt terminals is practically equal to $I \times R = 50 \times 0.004 = 0.2$ volt. With a shunt of half the former resistance or 0.002 ohm, the pressure applied to the movable

coil for the same current will be equal to $I \times R = 50 \times 0.002 = 0.1$ volt, or the coil will receive only one half the former current, and thus be deflected only to the middle of the scale. The range of the ammeter is now 0 to 100 amperes, or each scale reading must be multiplied by 2 to obtain the true value of the current when used with this shunt. In the same manner with a reduction of the resistance of the shunt to one-tenth of its original value, the range of the instrument is increased tenfold and the readings are multiplied by 10.

To determine the resistance of a shunt for measuring currents larger than the capacity of an ammeter, let

R = resistance of shunt required,
r = resistance of ammeter,
A = range of ammeter,
A_1 = desired range of ammeter.

Then

$$R = \frac{A}{A_1 - A} \times r. \quad \ldots\ldots\ldots\ldots \quad \textbf{(82)}.$$

The indicated readings obtained must be multiplied by $\frac{A_1}{A}$ to be correct.

Problem 96. — (1) What will be the resistance of a shunt required to increase the capacity of an ammeter from 150 to 600 amperes? Resistance of the instrument is 0.009. (2) What will be the multiplying power of the shunt?

By Formula (82)

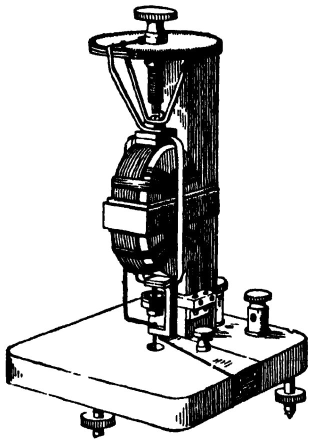
$$R = \frac{A}{A_1 - A} \times r = \frac{150}{600 - 150} \times 0.009 = 0.003 \text{ ohm.}$$

Multiplying power of the shunt $= \frac{A_1}{A} = \frac{600}{150} = 4$. Likewise by Formula (76)

$$n = \frac{G}{S} + 1 = \frac{0.009}{0.003} + 1 = 4.$$

214. Portable Dynamometer Ammeter-Electrodynamometer. — The dynamometer ammeter is an instrument for measuring current strength by the reaction between two coils, one of which is fixed and the other movable, and through which the current to be measured is passed. The operation and prin-

ciples involved are substantially the same as those used in the *electrodynamometer*, herein described, but the scale is graduated directly in amperes. The general appearance of a *Siemens dynamometer* is illustrated in Fig. 202, and the diagram of the circuits is shown in Fig. 203. The fixed coil CD, containing a number of turns of wire, is fastened to a vertical support. The movable coil AB of a very few turns of wire, is large enough to embrace the fixed coil when their planes are at right angles to each other, and is suspended by a strong piece of thread below the celluloid dial. The ends of this coil, being free to move, dip into two cups of mercury, located one above the other along the axis of the coil. Connections are made as indicated, so that the two coils are in series when connected to an external circuit. The planes of the coils should be at right angles to each other. When the current flows through both coils, the movable coil tends to turn, according to Law 2 (Lesson XV) for currents flowing parallel to each other.


Fig. 202. — Siemens Dynamometer.

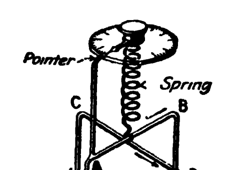


Fig. 203. — Connections of Siemens Dynamometer.

The force measured is the force which must be applied to keep the movable coil at right angles to the other against the turning effort due to the current. One end of a spring is rigidly fastened to the movable coil, and the other end terminates in a mill-headed screw on the face of the dial, which can be turned so as to apply torsion to the spring. The movable coil carries

an upwardly-extending pointer which swings between two stop pins on the dial and points directly to a fixed zero line when the coils are at right angles. To the torsion screw is attached a pointer which sweeps over a degree scale. When the movable coil is deflected against a stop pin, the torsion screw is rotated in a direction to oppose the current's action, and when the coil is brought back to its original position the number of degrees through which the torsion pointer was turned, is noted.

The current is directly proportional to the square root of the angle of torsion. For example, if with one current the number of degrees noted was 36 and with another current 144, then the currents are to each other as the square roots of 36 and 144, or as 6 is to 12, or one current is twice as strong as the other. To determine the current in amperes, the square root of the angle of torsion is multiplied by a constant found by calibration and furnished by the makers. The fixed coil is usually divided into two coils wound with a different number of turns, either of which is inserted in series with the movable coil, and the terminals are brought out to separate posts. Thus in measuring a current known to be between, say, one-tenth and 1 ampere, a certain pair of binding posts is used, and if between 1 and 100 amperes, the other pair of posts is used. This arrangement produces a double-scale instrument whereby both small and large currents can be measured with accuracy.

The Siemens dynamometer is an accurate instrument connected in circuit like an ammeter and has the advantage of being adapted for use with either direct or alternating currents. When used on a direct-current circuit more accurate results are obtained by taking the average value of two readings made with the current flowing in opposite directions.



Fig. 204 — Method of Connecting an Ammeter in a Circuit.

215. Connecting Ammeters in Circuit. — Since the total current to be measured in any circuit must flow through an ammeter, an *ammeter must always be connected in series with the circuit* and

between the generator and apparatus receiving current, as in Fig. 204. Suppose an ammeter whose resistance is 0.1 ohm is *incorrectly* placed in parallel with some incandescent lamps connected to a generator. The current that would flow through the ammeter if the pressure is 110 volts between the mains would be, by Ohm's Law, $I = \frac{E}{R} = \frac{110}{0.1} = 1100$ amperes, or enough to *totally destroy the instrument* by excessive heating, since the current-carrying capacity of the wire within the ammeter would be far below this value.

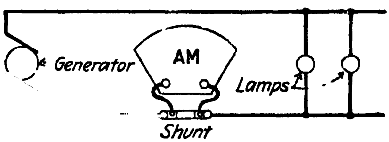


Fig. 205. — Connection of an Ammeter with External Shunt.

When a separate or external shunt is used with an ammeter the shunt is inserted in series with the circuit and the instrument connected across the shunt by the small-sized lead wire furnished for the purpose (see Fig. 205).

216. Measurement of E. M. F. and Potential Difference. — Consider first the following hydraulic analogy in which it is desired to measure the true water pressure at the point C in a pipe, Fig. 206, through which a current of water is flowing from A to B. Instead of using a spring gauge, which consumes no water in making the measurement, we will use a turbine wheel at point C. A jet of water from tank T forced against the wheel, which revolves at a particular speed for a given pressure at point C, say 1600 revolutions per minute, corresponding to a pressure of 50 pounds per square inch at C. *Is this the accurate pressure at point C, that is, the pressure that would be recorded by a spring gauge if inserted at point C? No.* The turbine in measuring the pressure will increase the flow of water at point C, as some water must necessarily discharge

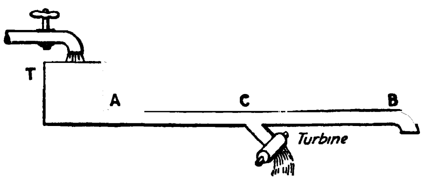


Fig. 206. — Measurement of Hydraulic Pressure.

through it. The accurate pressure will not be recorded, but a lower pressure will be noted than that which would exist were the turbine not connected. The increased current of water through the pipe from A to C, *due* to the turbine outlet, causes a greater loss in pressure. If the turbine were made exceptionally small and so sensitive that a very minute stream of water from the outlet would actuate it, it would more nearly record the true pressure at point C, since very little more current would then flow than when it was disconnected. This turbine pressure meter must, therefore, be constructed so that only a very small amount of water will be used by it in measuring the water pressure.

To measure the electrical difference of potential between two points requires a galvanometer constructed with a very high resistance, so that only a very minute current will flow through it, at the same time the current must be of sufficient strength to actuate the movable system, which is generally quite sensitive. *To measure electrical pressure some current must, therefore, be used, and the true pressure will be greater than the indicated pressure by an amount equal to the volts lost on the line and generator which are required to transmit the voltmeter current to the instrument. The less this current the more accurate the indication; consequently the best voltmeters have a very high resistance and their current is practically negligible.* When a voltmeter is placed in parallel with any part of a circuit the resistance of the circuit is practically the same as before, since the voltmeter resistance is so very high; the current in the circuit is not materially changed, and the calibrated indication records not the current in the circuit, or the current through the voltmeter, but the difference in pressure between the voltmeter terminals. The movement of its magnetic system, of course depends upon the current flowing through the voltmeter, but the scale is calibrated by applying known E. M. F.'s to its terminals and marking the position of the needle with reference to the scale for each particular pressure applied. In an ammeter the whole current passes through the instrument, or its shunt, and the instrument measures the current. A voltmeter measures the current flowing through it, but the *calibration is in terms of the pressure causing this current to flow.*

217. Construction of Voltmeters. — The same principles employed in the construction of ammeters (¶ 207 etc.) are employed in constructing voltmeters, the only difference being that the windings are of very fine wire, suitable to the small current that is to be carried, and that extra resistance coils are generally added in series with the voltmeter coils to produce an instrument of very high resistance, for the reasons already given.

218. Weston Direct-Current Voltmeters. — The same mechanical construction is employed in the Weston D. C. voltmeter as in this make of ammeter (¶ 212), except that resistance is connected in series with the movable coil. A double-range Weston Model 280 miniature voltmeter is shown in Fig. 207, suitable for use with pressures as high as 150 volts, and its internal connections are shown in Fig. 208. The 150-volt coil terminates in the two right-hand binding posts, and the current enters by the right-hand post marked +. A push-button in the lower corner serves to close the circuit. The resistance of the 150-volt coil is about 11,000 ohms, and there are 30 divisions on the scale, or one division per 5 volts. The 3-volt coil terminates in the right-hand and left-hand posts, and has a resistance of about 220 ohms. There are ten divisions on this scale per volt, or one-tenth volt per division. The double-range Weston standard portable voltmeter, Model 1 (Fig. 209), is a higher grade instrument than Model 280, and with it greater accuracy in voltage measurement may be had, since its internal resistance is higher and the scale is of greater length permitting a greater number of divisions for the full-scale length; a Model 1 voltmeter with a range of 150 volts would have a scale of 150 divisions or one division per volt, instead of 5 volts, as in Model 280.



Fig. 207. — Weston Double-range Model 280 Voltmeter.

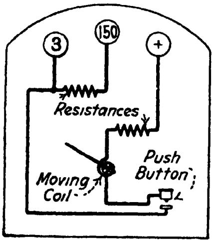


Fig. 208. Connections of Double-range Voltmeter.

In using a double-range voltmeter, *if in doubt about the value of the voltage* to be measured, *always use the higher-reading scale first,* then if the value is below the limit of the low-reading scale, the left-hand terminal may be readily changed to the other post. If 150 volts are directly applied to the low-reading or 3-volt posts, the instrument will be seriously damaged and probably the insulation destroyed by a larger current flowing through it than the windings will carry. For the same reason any voltmeter should not be subjected to a higher voltage than is indicated upon its scale.

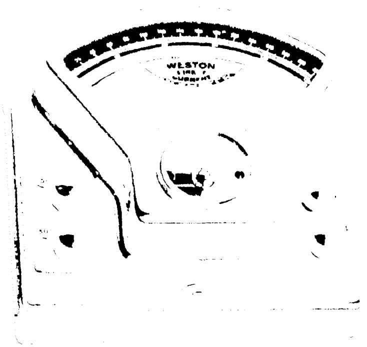


Fig. 209. — Model 1 Weston Voltmeter.

Voltmeters are calibrated by means of standard cells and are made up according to the range of the instrument desired, by means of the extra resistance to be added. In a *millivoltmeter* the scale is graduated to read in divisions representing one-thousandth part of a volt, or one millivolt. The Weston direct-current ammeter without its shunt, may be used as a millivoltmeter, and when a high resistance is placed in series with the movable coil the same instrument may be calibrated as a direct-reading voltmeter.

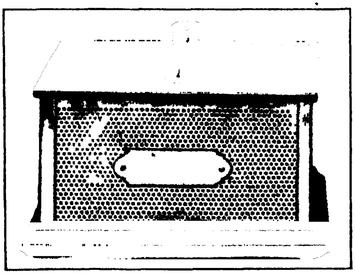


Fig. 210. — Multiplier.

219. Multipliers. — The high resistance connected in series with the movable coil of the direct-current instrument when it is to be used as a voltmeter, is called a *multiplier*, and if the instrument is to be used at all times as a voltmeter of

given range, this high resistance is placed inside the instrument case.

The range of any voltmeter may be increased to any practical limit by inserting a resistance in series with the voltmeter; commercial multipliers (Fig. 210) that are used for this purpose, consist of resistance coils placed in a portable case. Multipliers are usually constructed with the resistance coils adjusted for the voltmeter with which they are to be used, as the resistance coil inserted in series with it should be a multiple of the voltmeter resistance, and the reading of the voltmeter is then multiplied by a constant, such as 2, 5, 10, etc., in order to determine the voltage of the circuit.

A multiplier is of considerable value, in that it does away with the necessity of having a number of voltmeters of different ranges.

220. Connecting Voltmeters. — Voltmeters are connected directly across the line, the voltage of which is required, or in

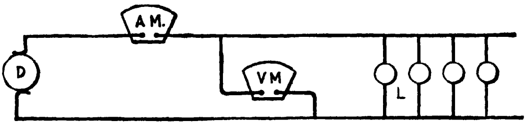


Fig. 211. — Connection of a Voltmeter and an Ammeter to a Circuit.

parallel with the conductor between the ends of which the potential difference is required. Figs. 101, 102, etc., illustrate the proper connection for measuring the potential in the different parts of a circuit. *A voltmeter is never connected in series with the line* and an *ammeter never across or in parallel with the line,* but always in series with it (see Fig. 211). The following problems will illustrate the reason for each particular connection.

Problem 97. — A 150-volt coil of a Weston voltmeter has a resistance of 15,000 ohms. What current will it receive when placed across a circuit of 100 volts P. D.?

By Formula (27) $I = \frac{E}{R} = \frac{100}{15,000} = 0.0066$ ampere.

Problem 98. — In Fig. 211 the generator D maintains 110 volts across the mains at the lamps L when 22 lamps are connected. Each lamp has a resistance of 220 ohms. What current will be indicated by the ammeter?

By Formula (30) $\text{J. R.} = \frac{R}{nq} = \frac{220}{22} = 10$ ohms.

By Formula (27) $I = \frac{E}{R} = \frac{110}{10} = 11$ amperes.

Problem 99. — Suppose the voltmeter in Problem 98 has a resistance of 15,000 ohms and is incorrectly placed in series with the lamps. What current will the lamps receive, assuming the potential to be 110 volts?

By Formula (27) $I = \frac{E}{R} = \frac{110}{15{,}000 + 10} = 0.0073$ ampere.

The lamps will not illuminate with this current since 10 amperes were required before

Problem 100. — Suppose the ammeter of Problem 98 has a resistance of 0.1 ohm and is incorrectly connected across the circuit, like the voltmeter in Fig. 211, what current will it receive if the P. D. is 110 volts?

By Formula (27) $I = \frac{E}{R} = \frac{110}{0.1}$ 1100 amperes.

Unless the ammeter had a current-carrying capacity of 1100 amperes it would be destroyed by the excessive heat caused by such a large current.

221. Potentiometer. — The potentiometer is an instrument used for comparing voltages with that of a standard cell by an arrangement of variable standardized resistances, a galvanometer, and a source of constant potential, such as a storage battery. The potentiometers made by different manufacturers differ in electrical and mechanical details, therefore, no attempt will be made to describe individual instruments. The principles of the potentiometer of whatever make may be readily understood from a study of Fig. 212, which shows a simple form of potentiometer consisting of a fine German-silver wire, AB, stretched between binding posts on a wooden base provided with a scale. Current is passed through this wire in one direction, A to B, from several

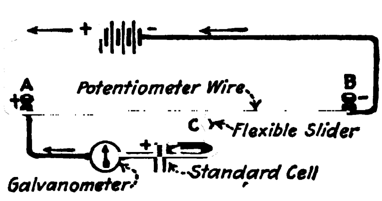


Fig. 212. — Connections of Potentiometer.

constant-current cells so that a constant P. D. will be maintained between the ends of the wire AB.

If this potential difference is known, the cell, the E. M. F. of which is to be determined, is connected in series with a galvanometer, and then in shunt with the potentiometer wire, so that its current will be in opposition to the potentiometer current. When the drop in volts on the length of the potentiometer wire is equal and opposite to the cell's E. M. F. no current will flow through the galvanometer, and its needle will stand at the zero position. This point is determined by sliding the movable contact C along AB, till balance of the needle is obtained at zero. Then the E. M. F. of the cell bears the same relation to the P. D. between the ends of the potentiometer wire AB, as the distance included between the cell terminals, AC, bears to the whole length of the potentiometer wire, AB.

Suppose the movable contact C touches the wire AB at a point where the volts drop along that wire is greater than the E. M. F. of the cell being measured, then, the greater E. M. F. of the upper cells will force a current in the reverse direction through the cell under test, since the two batteries are in parallel and although not directly across each other the cell under test is across enough of the voltage of the other cells to have its E. M. F. overpowered. The cells are delivering current through two parallel paths, one from A to B through the potentiometer wire, and the other from A to C through the cell under test and galvanometer against the E. M. F. of that cell: the latter current causes the galvanometer to be deflected in a certain direction. Now suppose the movable contact C is brought to rest on the wire at such a point that the volts drop from A to C is less than the E. M. F. of the cell; then, a current will flow out of the cell through the potentiometer wire from A to C and through the galvanometer, which is then deflected in the opposite direction. When the movable contact is brought to a point on AB that does not deflect the galvanometer, the volts drop from A to that point is exactly equal to the E. M. F. of the cell under test, hence no current can flow in either direction through that cell, the galvanometer needle standing at zero, and the potentiometer is said to be balanced.

If the E. M. F. of a cell is known and used as a standard of E. M. F., the E. M. F. of any other cell may be determined from this standard. The standard cell is first connected in the galvanometer circuit to the potentiometer wire (Fig. 212) and the distance, AC divisions on the scale, noted when balance is attained. The cell of unknown E. M. F. is then substituted for the standard, being connected in opposition as before, and the distance, say AD, noted when balance is obtained. The following relation then exists when AC equals the length on potentiometer wire balanced by the standard cell, and AD equals the length balanced by the cell of unknown E. M. F.:

$$\frac{\text{E. M. F. of standard}}{\text{E. M. F. of unknown}} = \frac{\text{length AC}}{\text{length AD}},$$

or

$$\text{unknown E. M. F.} = \frac{\text{E. M. F. of standard} \times \text{AD}}{\text{AC}} \quad . \quad . \quad \textbf{(83)}.$$

The potentiometer wire scale may be graduated to read in volts instead of inches. Thus, a wire 36 inches long with 3 volts P. D. across its ends would correspond to 12 inches per volt. When the potentiometer wire is graduated in volts, a voltmeter may be readily calibrated or recalibrated, by substituting it for the cell and galvanometer, and noting the deflections on the voltmeter scale due to different potential differences applied by moving the flexible slider along the potentiometer wire. The potentiometer in connection with a standard low resistance affords an accurate method for calibrating ammeters.

Problem 101. — In a potentiometer test a standard cell of 1.05 volts E. M. F. produced a balance when 12 inches of the potentiometer wire were included between its terminals What are the E. M. F.'s of two other cells that were measured if the potentiometer readings to produce balance were respectively 8 and 20 inches?

By Formula (83) $\text{unknown E. M. F.} = \frac{\text{E. M. F. of standard} \times \text{AD}}{\text{AC}}$

$$= \frac{1.05 \times 8}{12} = 0.7 \text{ volt} = \text{E. M. F. of the first cell.}$$

Also $\frac{1.05 \times 20}{12} = 1.75 \text{ volts} = \text{E. M. F. of the second cell.}$

QUESTIONS

1. What is the advantage of an ammeter of the stationary permanent magnet and moving coil type over one constructed to actuate upon the solenoid and moving iron principle?

2. What is the advantage of the stationary coil and moving iron type of instrument over the other type?

3. In a station shunt-type ammeter a pair of shunt leads are used which are the same length as those furnished with the instrument, but of a smaller size. How will this affect the meter's indications?

4. An ammeter coil with its leads has a resistance of 50 ohms, and the shunt has a resistance of 0.1 ohm. If 20 amperes are flowing through the circuit to which the shunted ammeter is connected, what current does the ammeter coil receive? *Ans.* 0.04 ampere.

5. It is desired to use an ammeter of only 50 amperes capacity in a circuit through which 150 amperes are flowing. How would you do this?

6. How much resistance would you use if the instrument in Question 5 had a resistance of 0.06 ohm? Make a sketch. *Ans* 0.03 ohm.

7. By what should the indications of the ammeter in Question 6 be multiplied in order to obtain the true reading?

8. A Siemens dynamometer is connected in series with some incandescent lamps and the torsion head must be turned through 121° to bring the movable coil to the zero position. Some lamps are then turned off and the angle indicated by the torsion head is 81°. What is the strength of current in each case if the constant of the instrument is 2? *Ans* 22 amperes; 18 amperes

9. What is the advantage of a dynamometer ammeter over one constructed upon the D'Arsonval principle?

10. What is the essential requirement in order to measure E. M. F. accurately, and how is it fulfilled in voltmeter construction?

11. Since the mechanical construction and the resistance of the movable coil of a Weston voltmeter and ammeter are both the same, what then is the essential difference in the instruments?

12. Give a numerical example to illustrate the use of a multiplier in extending the range of a voltmeter.

13. What is a potentiometer and for what is it used?

14. In a potentiometer test, balance of the galvanometer needle is attained with a standard cell of 1.05 volts for 210 divisions. For another cell the balance is attained at 430 divisions. What is the E. M. F. of this cell? Give a complete sketch. *Ans.* 2.15 volts.

LESSON XVIII

WATTMETERS AND WATT-HOUR METERS

Measurement of Power and Energy — Indicating Wattmeter — Thomson Watt-Hour Meter — Sangamo Direct-Current Watt-Hour Meter — Reading the Watt-Hour Meter — Questions.

222. Measurement of Power and Energy. — The electric power expended in a circuit is equal to the product of the voltage E, and the current I, or $P = E \times I$, Formula (54). These factors may be determined by a voltmeter and ammeter; and when the readings of the two instruments are multiplied together the result will give the true power expended in the circuit, provided the circuit is carrying a *direct* current. If, however, the current is alternating in character, the product of the volts and amperes only will not give the true power (¶ 333) unless the apparatus connected to the circuit is non-inductive, such as incandescent lamps. The power in either an alternating- or direct-current circuit may be measured by a *wattmeter*, which automatically multiplies the volts and amperes together, and will indicate the instantaneous value of the true power in either kind of circuit, regardless of whether the resistance connected in the circuit is inductive or non-inductive.

Meters for the measurement of electrical energy are called *watt-hour meters*, and these devices take care not only of the power taken by a load but also of the duration of that load. The energy supplied to a circuit by ¶ 142 is

$$\text{energy} = E \times I \times t,$$

or by ¶ 148 is

$$\text{energy} = P \times t.$$

If P is the power in watts and t is the time in hours, then the energy is expressed in watt-hours.

223. Indicating Wattmeter. — The indicating wattmeter measures the instantaneous values of the power in any circuit

to which it is connected, the power in watts being directly read from the scale, and it is, therefore, called an indicating wattmeter. Most wattmeters are constructed on the principle of the Siemens dynamometer, and operate upon the same principles as the dynamometer ammeter (¶ 214) but the two coils are not connected in series. The stationary coil, or *current coil*, is connected in series with the line like an ammeter and is wound with a few turns of heavy copper wire having a low resistance. The movable coil, or *voltage coil*, is wound with many turns of very fine wire and connected in series with a high resistance. The construction of the Weston dynamometer wattmeter is shown in Fig. 213. The two field coils, AA, are wound with wire which will permit the entire current to flow through them without raising their temperature appreciably, the terminals of these coils being brought out to two large binding posts. The movable potential coil B, mounted and constructed similar to the coil shown in Fig. 197, consists of a number of turns of fine insulated copper or aluminum wire and connected in series with a high resistance R, the terminals being brought out to independent binding posts shown at the right. A push-button switch, S, is inserted in the voltage-coil circuit. The movable coil thus corresponds to the voltmeter and is connected to any circuit in the same manner as a voltmeter.

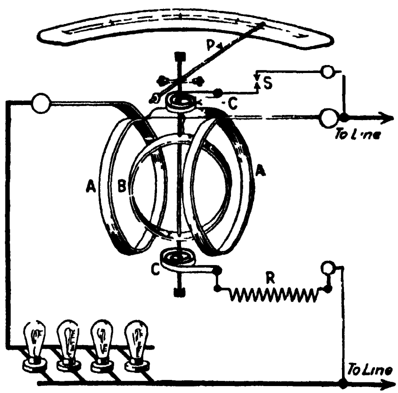


Fig 213. — Construction of Weston Indicating Wattmeter and its Connection in a Circuit.

The current in the voltage coil will vary as the potential difference between its terminals, and the current through the current coil will vary as the current in the circuit in which it is inserted. The force acting upon the movable coil depends

on the current through both coils, or directly upon the watts expended in them. The movable coil turns against the torsion of the springs CC, and its pointer P swings over a scale graduated in watts. The instrument is, therefore, direct reading, as in the case of a voltmeter. Fig. 213 shows the proper connections of the instrument for measuring the watts consumed by the incandescent lamps.

The Weston instrument requires no adjustment to secure a balance of the forces acting, and so momentary fluctuations are readily noted on the scale. This instrument can be used on any circuit and is rated according to the carrying capacity of the current coil and the potential to be applied across the voltage coil. For example, in a particular 1500-watt instrument the maximum current is 10 amperes and the maximum voltage is 150 volts. The capacity of the voltage coil can be increased to any desired range by the use of a multiplier.

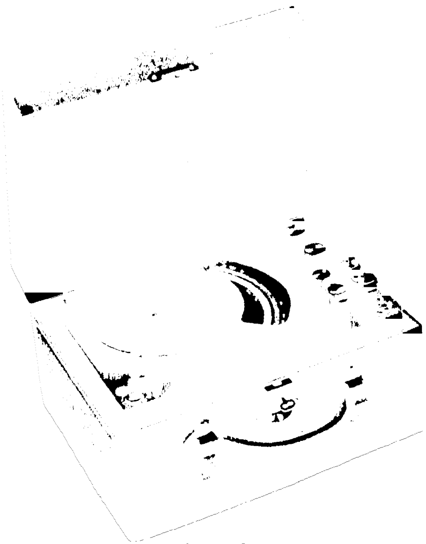

Fig. 214. — Portable Weston Wattmeter.

Fig. 214 shows the external view of a portable Weston electrodynamometer-type of indicating wattmeter. The two largest binding posts connect with the series coils through the four posts at the right-hand upper corner which enable the two coils to be connected in series or parallel with each other by means of short connecting links. The three small rubber-covered binding posts are for the potential wires and are marked ±, 150 and 75, thus providing two voltage ranges.

224. Thomson Watt-Hour Meter. — The consumption of electrical energy is paid for by the consumer at a fixed rate per

kilowatt-hour (¶ 148), therefore, it is necessary to have some form of meter that will measure the amount of electrical energy in watt-hours, or kilowatt-hours. Meters for measuring the amount of electrical energy are sometimes called integrating wattmeters, since they sum up the work done during successive intervals, but are more properly termed watt-hour meters.

The indicating wattmeter gives the instantaneous values of the watts expended in a circuit, just as a voltmeter indicates the momentary pressure in volts. To find the watt-hour consumption of electrical energy by such a wattmeter, it would be necessary to multiply the average of a number of readings taken during a given time, by that time, expressed in hours (¶ 148). As the name implies, the readings of a watt-hour meter gives the total watt-hour consumption of energy, or it automatically multiplies the average of the instantaneous indications by the time. Its principle of operation is that of the Siemens dynamometer (¶ 214) but the movable coil rotates. The method of producing this rotation may be demonstrated as follows:

In Fig. 203 continuous rotation of the coil AB around the coil CD could be produced, if, at each instant the coil AB became parallel to CD, the current were automatically reversed through it. With the single turn and a strong current, sufficient repulsive force would be produced to move it through 180°; if the current be now reversed it will receive a similar impulse and will be repelled through another 180°, and so on. There will thus be two reversals and two impulses given to the movable coil each revolution, and continuous rotation produced. The force producing the rotation will still be dependent upon the current in both coils as in the dynamometer. A uniform force for producing rotation would require several coils similar to AB arranged about a vertical axis, with their planes at angles to each other, so that as one coil moved away from the stationary coil another would take its place. Such an arrangement would be practically a motor, the moving coils forming the *armature* and the stationary coil the *field*. A worm on the armature shaft engaging with the train of wheels of a cyclometer dial would record the number of revolutions, and since this number in an hour depends on the currents through the coils during that time the cyclometer dial could be calibrated in watt-hours, provided the speed were proportional to the power consumed.

The Thomson watt-hour meter, of which an interior view is shown in Fig. 215 is a simple type of motor, driven by the electrical energy which it is to measure; its speed of rotation

during any period is proportional to the power in watts delivered to the circuit during that time. The movable coil or armature revolves between two stationary coils with its axis at right angles to the axes of these coils. The movable coil is a spherical armature (Fig. 216) without an iron core, and the current through its coils is reversed automatically by the commutator, thus causing it to revolve. Current is led to the commutator by silver-tipped contacts or *brushes*. A worm on the upper end of the armature shaft engages a set of wheels which records the watt-hours on a dial. The armature is very light and delicately poised between jewel centers, so that the friction is reduced to a minimum.

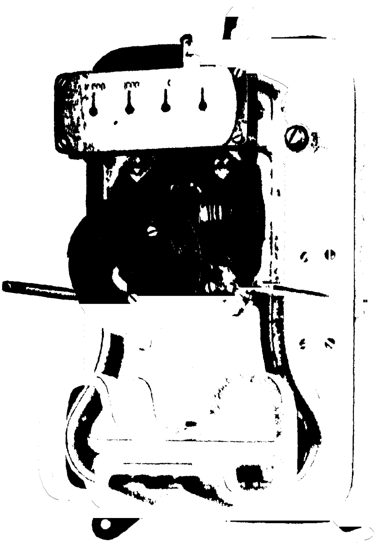


Fig. 215. — Thomson Watt-hour Meter.

The field of the watt-hour meter is produced by current in the stationary coils AA, placed one on either side of the armature B and connected in series with the line to which the meter is connected (Fig. 217). The field strength is strictly proportional to the current in the main line, since there is no iron in the field. The armature (in series with a comparatively high resistance) is connected by means of the commutator and brushes across the line, just like the voltage coil in the indicating wattmeter, so that the current in the armature is proportional to the voltage across the line. Consequently the torque (turning effort) of the armature must be proportional to the product of the voltage and the current, or to the watts expended in the load.

In series with the armature and resistance R (Fig. 217) is also connected an adjustable shunt field coil C, so placed as

to strengthen the field set up by the main field coils. The function of this coil is to compensate for the slight friction in the rotating armature, and when properly adjusted, its position is such that the field created by it will not cause rotation of the armature when there is no current in the main field coils, but with the smallest current in the main coils, its field will just overcome the friction in the armature and cause it to rotate. If the meter runs when no current is being used, causing the meter to register more energy than the consumer actually used, the meter is said to "creep."



Fig. 216. — Armature, Commutator and Brushes of Watt-hour Meter.

This will occur if the compensating coil C is too close to the main field coils. The coil is adjustable in a plane parallel to that of the main field coils, so that it can be moved to and fro as the need may be.

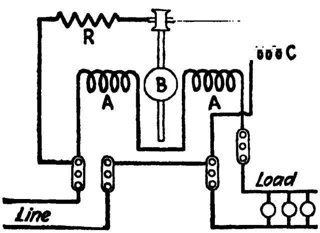


Fig. 217. — Circuits of Thomson Watt-hour Meter.

Since no iron is used in the magnetic circuit, the field is weak and the armature will develop little or no counter electromotive force (¶ 313). The armature current, therefore, is independent of the speed of rotation, and is constant for any definite potential applied at its terminals. Under these conditions the armature would revolve at an exceptionally high speed, if there were no retarding force applied

to the armature; therefore, in order to reduce the speed and secure correct registration by the meter it is necessary to provide some means for making the speed proportional to the torque. This is accomplished by applying a load or drag, the strength of which varies directly as the speed. Such a controlling force is obtained by causing an aluminum or copper disk attached to the armature shaft to rotate between the poles of stationary permanent horseshoe magnets, and cutting their magnetic lines of force as it revolves. Eddy currents (¶ 263) are induced in the disk, and the reaction of their magnetic field tends to retard the rotation. The amount of this retarding force or drag, is directly proportional to the speed of rotation. Since the torque causing the armature to rotate is directly proportional to the magnetic fields of the currents in the two coils, and the retarding torque is also proportional to the magnetic field set up, the armature must rotate at such a speed that the electromagnetic driving torque is exactly equal to the electromagnetic retarding torque. Then in a given length of time, the number of revolutions of the armature, and, therefore, the travel of the dial hands, will be proportional to the energy supplied.

Watt-hour meters are made in different sizes according to the current-carrying capacity of the current coil. The amount of extra resistance in the armature circuit depends on the voltage to which it is to be subjected. These meters are extensively used on commercial motor circuits and in individual house electric-light service, and are sensitive enough to record the energy through even a small-sized lamp when connected to the supply circuit.

225. Sangamo Direct-Current Watt-Hour Meter. — The Sangamo direct-current watt-hour meter is a mercury type of meter, somewhat similar in principle to the direct-current commutator type, but instead of having a moving coil and commutator, its armature consists of a copper disk which revolves in a mercury chamber, the mercury forming part of the circuit. This arrangement practically eliminates commutator friction, and the armature is floated in the mercury chamber. The principle of operation may be understood by referring to Fig. 218, which shows the relations of the various

parts, and also the voltage and current circuits of the meter. An electromagnet with poles N-S is energized by the potential coil or shunt winding SC, connected across the line wires. The mercury chamber M is made of insulating material and has molded in it the contact ears E_1 and E_2 diametrically opposite each other, and also has molded in it above the armature space a spirally-laminated soft steel ring D, which acts as a return for the magnetic lines of force from the electromagnet N-S. The copper disk A is secured to the shaft S, which carries the worm W to drive the recording mechanism; at the upper end of the shaft is secured the aluminum disk B, revolving between the poles of the permanent magnets F F, for regulating the armature speed. The shaft is supported at the upper end by a jewel bearing. One end of each of the series coils CT connects to the mercury by the ears E_1, E_2; the other ends of the winding connecting one to the line and the other to the load. The function of this series winding is to strengthen the field of the electromagnet as the load increases, and compensates for a falling off in speed due to increased mercury friction. From Fig. 218 it will be seen that the magnetic flux produced by the potential coil SC cuts or passes through the copper disk A, in order to complete its path through the soft steel ring D from the N-pole to the S-pole below. The disk, being in series with the load, is carrying a current which, due to the position of the contact ears, passes across the magnetic field from the magnet poles N-S, at right angles to this field. Since a conductor free to move and carrying a current whose direction of flow is at right angles to a fixed field will tend to move out of that field, the disk A moves from its initial position, and then the current entering at a new point on the periphery of the disk, causes it to be again impelled for-

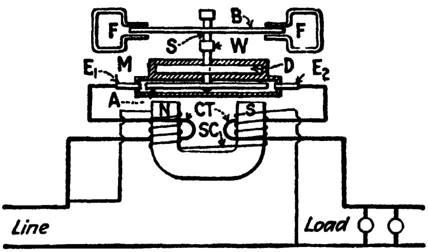


Fig. 218. — Arrangement of the Parts and Circuits of a Sangamo D. C. Watt-hour Meter.

ward; this constant change in point of current entrance to the disk producing a continuous rotation. The torque is proportional to the current in the disk and to the magnetic field, the latter being proportional to the voltage of the circuit, therefore the torque is proportional to the power in watts. The speed is rendered proportional to the torque by means of the aluminum disk B as explained in ¶ 224.

Compensation of friction on light loads is provided for in this meter, but not shown in Fig. 218, by an adjustable shunt circuit connected across the armature at E_1 and E_2. This

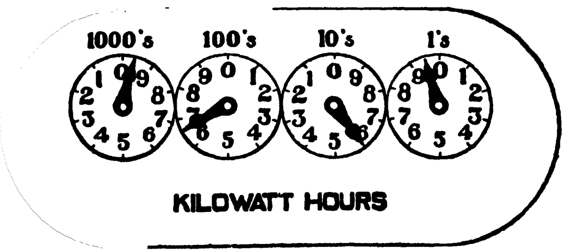


Fig. 219. – Registration Dials of a Watt-hour Meter.

shunt circuit consists of a thermo-couple in series with an adjustable resistance; the thermo-couple is operated by a heating coil connected in series with the winding SC. The E. M. F. produced by the thermo-couple sends a current through the disk, thereby producing sufficient torque to overcome friction under light loads.

226. Reading the Watt-Hour Meter. — The dials of an electricity or watt-hour meter are graduated in watt-hours or kilowatt-hours and read like the dials on a gas meter. The unit in which the measurement is made is usually marked on the dial face and would be watt-hours or kilowatt-hours. The dial face may contain four circles, as in Fig. 219, or five circles; however, the principle of reading either of them is exactly the same. In Fig. 219 the dial face contains four circles, the figures marked above them are the amounts of energy recorded by a movement of the pointers over one division of the corresponding circles; therefore one revolution of a pointer denotes ten times the amount marked above its circle. One revolution of the

pointer on any circle moves the pointer on the next circle to the left, one division; to illustrate: a complete revolution of the pointer on the "10" circle moves the pointer on the "100" circle one division and registers 100 kilowatt-hours. The pointers on the first and third circles turn clockwise, while the pointers on the second and fourth circles turn counterclockwise.

In deciding the reading of a pointer, the pointer before it (to the right) must be noted, for unless the pointer before it has reached or passed "o," or in other words, completed a revolution, the other has not completed the division on which it may appear to rest. For this reason ease and rapidity are gained by reading a meter register from right to left. To correctly read the sum indicated on the dial face of a watt-hour meter, begin with the circle on the right-hand side of the dial face, that is, the circle of lowest capacity, then note the readings of the second and third circles, and so on, putting the numbers down in their proper order, or from right to left.

In Fig. 219 the statement of the register is 9659 kilowatt-hours. Wattmeter readings are cumulative, and to learn the amount of electrical energy consumed during any interval of time, it is necessary to subtract the reading at the beginning of the period from that taken at its close. Meters of large capacity are subject to a multiplying constant, such as 10, or some multiple thereof, and this value appears on the dial face; the registration of such meters must be multiplied by the constant to determine the actual consumption of electrical energy.

The constant is the measure of the mechanical adjustment in the register of the meter and is the ratio of the true energy consumption and the registration of the dial hands. The constant is used to avoid a high speed of rotation, the adjustment is made by the manufacturer of the meter.

QUESTIONS

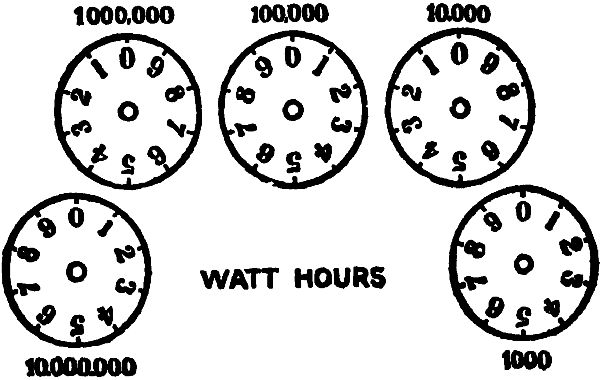
1. Describe an indicating wattmeter.
2. Sketch in detail a Weston indicating wattmeter connected to a motor circuit so as to indicate the power being absorbed.
3. What is the difference between an indicating wattmeter and a watt-hour meter?
4. What is the principle of operation of a Thomson watt-hour meter?

5. How is the proper speed of rotation and correct registration obtained in the watt-hour meter?

6. A Thomson watt-hour meter is found to register a small amount of energy after the load has been disconnected. What is the trouble and how could it be remedied?

7. How does the Sangamo watt-hour meter differ from the Thomson watt-hour meter, and upon what principle does it operate?

8. Indicate the positions of the pointers on the dials below for a reading of 253,400 watt-hours.



LESSON XIX

MEASUREMENT OF RESISTANCE

Resistance Standards — Voltmeter and Ammeter Method of Measuring Resistance — Substitution Method of Measuring Resistance — Comparative Drop Method of Measuring Resistance — Voltmeter Method of Measuring Resistance — Wheatstone Bridge Method of Measuring Resistance — The Slide-Wire Bridge — Commercial Wheatstone Bridges and Portable Testing Sets — Ohmmeters — Questions and Problems

227. Resistance Standards. The value of an unknown resistance may be measured by a direct application of Ohm's Law, or by comparison with a "Standard" resistance, using the methods given below.

The Standard ohm defined in ¶ 62, as the resistance offered by a uniform column of mercury 106.3 centimeters long and weighing 14.4521 grams, is not a convenient standard with which to compare resistances in practice, therefore secondary standards, made of wire and standarized with great precision, are used commercially. The wire used must have a fairly high resistivity and a low temperature coefficient; therefore, these standards of resistance are made of manganin wire, which possesses these qualities. A number of resistance standards of various values when assembled in a single case are collectively called a resistance box, or sometimes a rheostat (¶ 75).

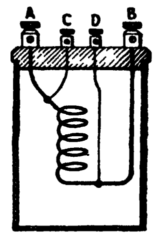


Fig. 220. — Standard Resistance.

Very low resistance standards of large current-carrying capacity have their coils immersed in oil and provided with four terminals, as in Fig. 220. In this diagram A and B are the current terminals and are connected in series with the circuit, C and D are the potential terminals to which is connected the voltmeter or whatever potential device may be used

228. Voltmeter and Ammeter Method of Measuring Resistance. — This is a very simple method for measuring an unknown resistance directly by Ohm's Law, requiring an ammeter, a voltmeter and a source of electricity. The unknown resistance, X, is connected in series with an ammeter and source of electricity as in Fig. 221, and a voltmeter is then connected across the terminals of that resistance. Simultaneous readings of both instruments are made, the value of the unknown resistance is then found by Ohm's Law.

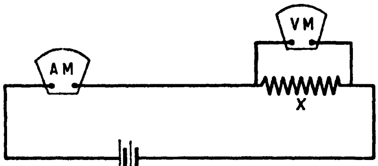


Fig. 221. - Voltmeter and Ammeter Method.

This method of resistance measurement is well adapted to practical work in the repair shop, the laboratory, or the central station for measuring the resistance of the field and armature windings of generators and motors, the resistance of incandescent lamps while burning, or the resistance of almost any electrical device. Fig. 222 illustrates the method of measuring the resistance of an incandescent lamp while burning, the ammeter is in series with the lamp, the voltmeter is connected across the lamp, and the resistance is then found by applying Ohm's Law.

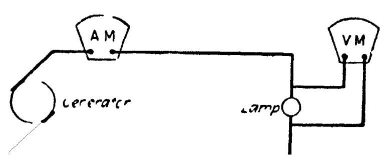


Fig. 222. -- Measuring the Resistance of a Lamp.

In using this method to measure the resistance of a wire or coils of wire, care must be taken not to pass a greater current through the wire than it will carry without undue heating otherwise a higher resistance than the true one will be measured. A millivoltmeter will give greater accuracy when the resistance is quite low, as, for example, the series field of a large dynamo which may have a resistance of perhaps 0.001 ohm. On the other hand, when the method is applied to high resistances the current will usually be small and a milliammeter can be used to advantage.

Problem 102. — What is the resistance of the object X (Fig. 221) if the respective readings of ammeter and voltmeter are 4 and 36?

By Ohm's Law $R = \frac{E}{I} = \frac{36}{4} = 9$ ohms.

Problem 103. — The resistance of a bonded rail is to be measured by the voltmeter-ammeter method. The current through the rail and its copper joint is 500 amperes, the drop across the joint is 25 millivolts. What is the resistance in microhms?

By Ohm's Law $R = \frac{E}{I} = \frac{0.025}{500} = 0.00005$ ohm.

By Formula (1) $0.00005 \times 1{,}000{,}000 = 50$ microhms.

229. Substitution Method of Measuring Resistance. (*Galvanometer and adjustable rheostat required.*) — The unknown resistance X and the galvanometer G are connected in series with a source of continuous current (Fig. 223) and the galvanometer deflection is noted. Then substitute for the unknown resistance X, a known adjustable resistance R (such as a resistance box) by moving switch S, and adjust the value of R until the galvanometer deflection is the same as before. The resistance in the rheostat is now equal to the unknown resistance, since the current through the galvanometer is the same as before, and the pressure is also the same.

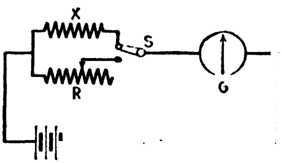


Fig. 223. — Substitution Method.

Problem 104. — With the connections shown in Fig. 223 the deflection of the galvanometer with the unknown resistance in circuit was 25 divisions. With the rheostat substituted it was found necessary to unplug 47 ohms to obtain a deflection of 25 divisions. What is the resistance of the device? *Ans.* 47 ohms.

230. Comparative Drop Method of Measuring Resistance. (*A standard resistance or graduated rheostat and a voltmeter required.*) — This method is very convenient for many practical measurements. No ammeter is required. The standard and unknown resistances are connected in series and to a source of continuous current (Fig. 224). The drop in volts across each resistance, as measured by the voltmeter, is directly proportional to its resistance, since the current is the same through

both resistances. The drop on the standard resistance also bears the same relation to the drop on the unknown resistance as the value of the standard resistance bears to the value of the unknown resistance, or, calling the unknown resistance X, then:

$$\frac{\text{drop on standard}}{\text{drop on X}} = \frac{\text{resistance of standard}}{\text{resistance of X}},$$

or

$$X = \frac{\text{resistance of standard} \times \text{drop on X}}{\text{drop on standard}} \qquad (84).$$

A high-resistance galvanometer, the deflections of which are proportional to the current, may be used instead of the voltmeter and the value of the deflection substituted in the formula. The most accurate results are obtained when the standard resistance is selected in value as near as possible to the supposed value of the unknown resistance. If the current is not very steady several readings should be taken for each measurement and the average value used in the formula. With suitably selected standards this method is adapted for measuring either high or low resistances with accuracy.

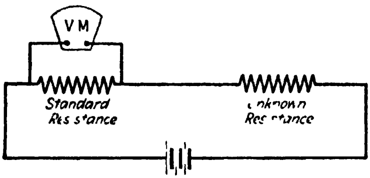


Fig 224 --Comparative Drop Method.

Problem 105. With the connections shown in Fig. 224 the drop on the standard resistance of 5 ohms was 2 volts, while the drop on the unknown resistance was 10 volts; what is the value of the unknown resistance?

By Formula (84) $X = \frac{5 \times 10}{2} = 25$ ohms.

231. Voltmeter Method of Measuring Resistance. (*Voltmeter of known resistance required.*) — This method is especially adapted for measuring high resistances, such as insulation resistance of wires, etc. The voltmeter is connected in series with the unknown resistance X across the source of E. M. F., which should be as high as possible, within the limits of the voltmeter scale. A switch or key K is connected across the resistance X so that it may be short-circuited, Fig. 225. A

reading of the voltmeter is taken when the key is closed, and the value of the indication is represented by the letter V. With switch K open, the unknown resistance X is inserted in series with the voltmeter, and the voltmeter indication is again noted, calling it V_1.

With the switch K closed, the voltmeter reading V represents the voltage across itself, that is, across its resistance r. When the switch is open the voltage at the generator terminals is distributed across resistance X and the voltmeter in direct proportion to their separate resistances, since they are both in series across the generator terminals (¶ 230). In this condition the reading V_1 when the switch K is open also represents the voltage across the voltmeter, but the difference between V and V_1 represents the voltage across the resistance X. Since with the switch open a simple series circuit is formed in which the resistance of each part is proportional to the voltage across that part, the resistance of X may be calculated from the following proportion:

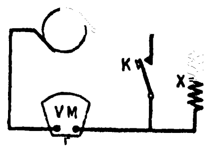


Fig. 225. — Measurement of Resistance by the Use of a Voltmeter.

$$X : r = V - V_1 : V_1, \quad \text{or} \quad \frac{X}{r} = \frac{V - V_1}{V_1};$$

therefore,

$$X = r\left(\frac{V}{V_1} - 1\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(85).}$$

Problem 106. — When the voltmeter in Fig. 225 is directly connected across the source of E. M. F. it indicates 110 volts; when placed in series with the unknown resistance it indicates 4 volts. What is the value of the unknown resistance if the voltmeter has a resistance of 150,000 ohms?

By Formula (85) $X = r\left(\frac{V}{V_1} - 1\right) = 150{,}000\left(\frac{110}{4} - 1\right) = 150{,}000 \times (27.5 - 1) = 150{,}000 \times 26.5 = 3{,}975{,}000$ ohms, or 3.975 megohms.

A modification of this method suitable for the measurement of very high resistances is the so-called *direct deflection method* which employs instead of the voltmeter of Fig. 225 a sensitive galvanometer whose constant is known (Lesson XVI). No short-circuiting key K is used, otherwise the circuit is the same

as Fig. 225. Thus, if the galvanometer gives a deflection of 12 divisions for one volt through 1 megohm, then if 500 volts are used in measuring the insulation of cable and the galvanometer gives 150 divisions deflection, it is evident that the insulation resistance of the cable is

$$\frac{500}{1} \times \frac{12}{150} = 40 \text{ megohms.}$$

232. Wheatstone Bridge Method of Measuring Resistance.— To measure resistance with extreme accuracy, the Wheatstone bridge is universally used. The Wheatstone bridge is constructed in several different forms which will be described in the following paragraphs. The simplest form and one in which the circuits are easily traced is the lozenge form illus-

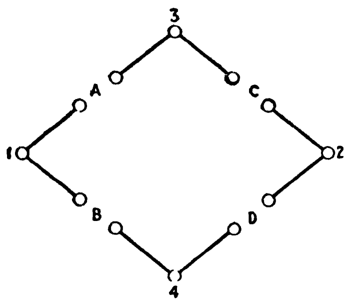


Fig. 226 — Lozenge Form of Wheatstone Bridge.

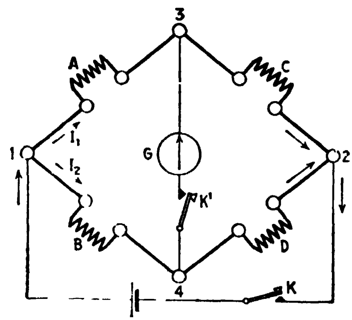


Fig. 227. — Circuit of Wheatstone Bridge.

trated in Fig. 226. It consists of a diamond-shaped arrangement of metallic wires or strips provided with binding posts as shown, the wires being of sufficient area to insure negligible resistance.

To make a resistance measurement with the lozenge bridge, connections are made as in Fig. 227 in which A, B, C and D are called the *arms* of the bridge. The gaps in the A and B arms are bridged by standard resistances, to the C arm is connected a rheostat, and the unknown resistance is connected to the D arm. A current from a battery is sent into the bridge at the post 1, at which point it divides into two parts: one part

flowing in the branch circuit consisting of resistances A and C, the other part flowing through the branch consisting of resistances B and D, the current from both branches uniting at point 2 to return to the battery. A galvanometer G is connected between the two branch circuits at points 3 and 4, and keys K and K′ are connected respectively in the battery and galvanometer circuits.

The theory of the bridge is as follows: when a current flows through a circuit there is a drop in potential across each part of the circuit proportional to the resistance of that part and to the current in it. With the galvanometer key K′ open, the current will be the same through all parts of the upper branch circuit of Fig. 227, say I_1; then the drop of potential from 1 to 3 is the product of resistance A ohms and of I_1 amperes, or $A \times I_1$ volts, in accordance with Ohm's Law, and likewise, the drop from 3 to 2 is $C \times I_1$ volts. Again, if the current in the lower branch circuit be I_2, then the drops across coils B and D will be respectively $B \times I_2$ and $D \times I_2$ volts. These four drops of potential will usually have different values; for example, the potential between 1 and 3 will be different from that between 1 and 4, in consequence there will be a difference of potential from 3 to 4. On depressing the galvanometer key K′, a current will flow through the galvanometer as a result of that potential difference, and the moving element of the instrument will be deflected. If, however, the resistances are so proportioned with respect to each other that the drop from 1 to 3 (namely $A \times I_1$) will equal the drop from 1 to 4 (namely $B \times I_2$) then on closing the key K′ no current will flow through the galvanometer because there is no difference of potential between its terminals, 3 and 4. When this condition obtains, it is evident that

$$A \times I_1 = B \times I_2,$$

and also

$$C \times I_1 = D \times I_2.$$

Dividing member by member, there results

$$\frac{A \times I_1}{C \times I_1} = \frac{B \times I_2}{D \times I_2},$$

from which

$$\frac{A}{C} = \frac{B}{D},$$

which expresses the relationship between the four resistances in order that the galvanometer will show no deflection. In practice the resistance in the A and B arms, called the *bridge arms*, are adjusted to a certain ratio dependent upon the approximated value of the unknown resistance, and the varia-

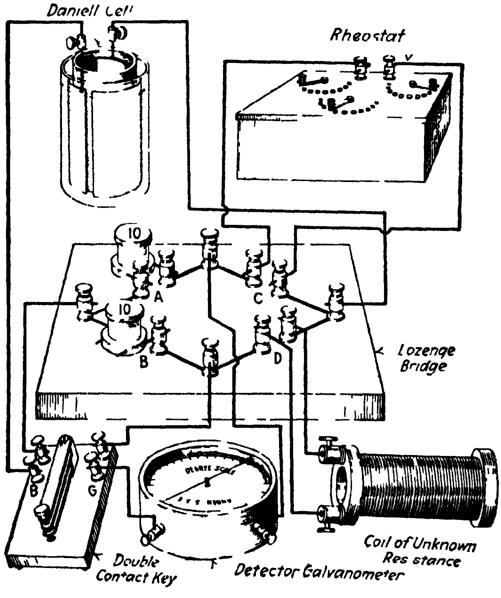


Fig 228 — Student's Wheatstone Bridge (Lozenge Pattern) with the Apparatus Required for Measuring Resistance

ble resistance in the C arm is adjusted until, on closing key K′, the galvanometer gives no deflection, and the bridge is said to be *balanced*. If the value of A, B and C are known, the value of D can be determined by the following formula deduced from the foregoing proportion:

$$D = \frac{B \times C}{A} \quad \dots\dots\dots\dots\dots \quad \textbf{(86).}$$

The connections and apparatus required for making a resistance measurement with the lozenge form of bridge are illustrated in Fig. 228. The apparatus illustrated comprises the following parts: Daniell cell, adjustable graduated rheostat, two standard resistance spools (those shown have ten ohms each), detector galvanometer, the resistance to be measured (in this case a solenoid), and a double-contact key which combines the two separate keys shown in Fig. 227. This double-contact key practically consists of two button switches mounted one over the other on the same base; the upper switch is connected to the two adjacent posts marked B, and closes the battery circuit when a slight pressure is applied. The lower switch is connected to the other two posts marked G, and is inserted in series with the galvanometer (Fig. 228). When the knob is depressed two independent circuits are closed, first the battery and then the galvanometer circuit. On releasing the knob the galvanometer circuit breaks first. The battery circuit must always be closed before the galvanometer circuit in order to allow the current to become steady before closing the galvanometer key, hence the use of the double-contact key.

Six resistance standards, made up in convenient form and provided with wire terminals to slip into the posts of the A and B arms, are furnished with this particular bridge. There are two 1-ohm, two 10-ohm, and two 100-ohm spools; the proper selection of these standards is given later.

The balancing of potentials in a Wheatstone bridge may be practically illustrated by the use of a voltmeter and a number of incandescent lamps connected in the manner shown in Fig. 229, Experiment 79.

Experiment 79. — In Fig. 229 there are shown nine 50-volt carbon-filament lamps connected so as to form the four arms of the Wheatstone bridge, and 125 volts from a generator are applied to the points 1 and 2. Each lamp will be assumed to have a constant resistance of 50 ohms irrespective of the amount of current flowing through it.

In the upper branch of the divided circuit, there are two lamps in series in the A arm, making a total resistance of 100 ohms, and in the C arm there are two lamps in parallel, making a joint resistance of 25 ohms; therefore, the total resistance of A and C in series is 125 ohms. With 125 volts maintained across points 1 and 2, the branch AC will receive one

ampere, and the potential across A will be 100 volts and across C 25 volts The lamps in the A arm will burn at normal candle power, but the lamps in the C arm will burn dimly since they get only 0.5 ampere each. In the lower branch the B arm has 4 lamps in series making its resistance 200 ohms, and D has one lamp of 50 ohms; therefore, the total resistance of B and D in series is 250 ohms and the current through this branch will be 0.5 ampere, all lamps burning dimly. The potential across B will equal 100 volts, the same as the potential across A, and that across D will be 25 volts, or the same as the potential across C. If a voltmeter is now connected to points 3 and 4, as shown, it will not give any appreciable deflection, since the potential across 1–3 is the same as that across 1–4, namely 100 volts; and the potential across 3–2 is the same as that across 4–2, or 25 volts.

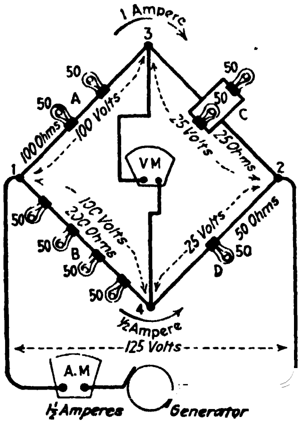


Fig. 229. — Lamp Analogy of the Wheatstone Bridge.

This balancing of potentials is due to the fact that the value of resistance A bears the same ratio to that of B, as the value of resistance C bears to that of D The student should measure with the voltmeter the voltage across each arm of the bridge, and across points 3–4 to verify the above statement; then take similar measurements, after having unbalanced the potentials by taking one of the lamps in the C arm out of that circuit. When the voltmeter is connected to points 3 and 4 under the latter condition it will show a difference of potential to exist between these two points.

The foregoing experiment may be modified by using one 110-volt lamp in each arm of the bridge (all lamps of the same type) and using 110 volts across points 1 and 2. If all the lamps have the same resistance the bridge will be balanced and a voltmeter will not indicate when connected across points 3 and 4; the bridge may be unbalanced by replacing the lamp in one arm by one of a different type or of different voltage.

Operating the Bridge. — Make the bridge connections as given above and shown in Fig. 228. Suppose the unknown resistance, a coil of wire connected at D, to be about 20 ohms. Connect a 10-ohm spool in arms A and B. See that all connections are bright and tight. Insert resistance in the graduated rheostat to the value of what you approximate D will measure. Depress the double-contact key and note the ***direction*** of deflection of the galvanometer needle, say ***to the left.***

Release the key and add more resistance to circuit C. If, on depressing the key, the deflection is still *to the left but less than before*, release the key and *add more resistance*. If, on the next trial, the needle swings *to the right, too much resistance has been added* and some must be taken out of the rheostat circuit. Proceed in this manner till a balance is obtained. In the above case the needle swinging to the *right of zero* means that the rheostat's resistance *must be decreased* while the needle swinging to the *left of zero* indicates *too low a resistance* in the rheostat. With the same pole of the battery always connected to the same bridge post, and likewise with the galvanometer, this relation of the needle's deflection will always hold good, and in such a case could be marked on the instrument, as is done in the portable bridge sets.

Suppose a balance is obtained when 18 ohms are in the rheostat circuit, then by Formula (86)

$$D = \frac{B \times C}{A} = \frac{10 \times 18}{10} = 18 \text{ ohms.}$$

When the A and B arms have equal resistances they will always cancel in Formula (86), so that the unknown resistance is then equal to the amount inserted in the rheostat circuit, and can be read directly from it without reference to the formula. With equal resistances in the A and B arms, which should always be as near as possible to the unknown resistance, the maximum resistance that the bridge will measure is limited to the resistance contained in the rheostat.

To Measure a High Resistance. — The value of the resistance in the A arm should be low, since from Formula (86) it will be observed that the value of the resistance in the A arm is the divisor; consequently if a low-resistance spool is selected for it and a high-resistance spool for the arm B, the quotient will be high. For example, let B = 100 ohms and A = 1 ohm, and suppose that balance against some unknown resistance was obtained when 150 ohms had been inserted in the rheostat, then

$$D = \frac{B \times C}{A} = \frac{100 \times 150}{1} = 15{,}000 \text{ ohms,}$$

or the bridge is capable of measuring a much higher resistance than the rheostat may contain.

To Measure a Low Resistance. — The A arm should have a large resistance and B small, hence select spools for arms A and B accordingly. For example, let arm B = 10 ohms and A = 100 ohms, and assume that balance obtains against some unknown resistance when 2 ohms are inserted in the rheostat, then

$$D = \frac{B \times C}{A} = \frac{10 \times 2}{100} = \frac{20}{100} = 0.2 \text{ ohm},$$

or the bridge will measure a much lower resistance than the rheostat may contain. Suppose a balance is obtained in another measurement when B = 1, A = 100 and C = 3; then

$$D = \frac{B \times C}{A} = \frac{1 \times 3}{100} = 0.03 \text{ ohm}.$$

The selection of spools for the greatest accuracy in measurement depends upon the resistance of the galvanometer and the internal resistance and E. M. F. of the cells used with the bridge, so that no specific rule can be given beyond the varying of the ratios, as here given.

233. The Slide-Wire Bridge. — A simple form of slide-wire bridge for measuring resistance is depicted in Fig. 230. A piece of high-resistance wire of uniform cross-section is stretched between binding posts 1 and 2, and takes the place of resistances A and C in Fig. 227. Directly under the wire is a double scale graduated in 1000 equal divisions with zero at either end, to facilitate taking readings from either point, 1 or 2. The letters and figures indicate the same points on this form of bridge as on the lozenge form of Fig. 227. Both forms of bridge operate upon the same principle, but in the slide-wire form the potentials are balanced by moving the slider S along the wire between posts 1 and 2, thus decreasing or increasing the resistances of A or C as desired. A standard resistance spool is inserted in the binding posts at B (Fig. 230) and the unknown resistance is connected to the posts at D. The battery is connected across points 1 and 2, as before, and one galvanometer terminal is joined to post 4 while the other is connected to the flexible-wire slider S. This slider is moved along the wire 1-2 till some point, as 3, is found where the galvanometer needle is not deflected; then the length 1–3, or

A, and length 3-2, or C, are read from the scale. The value of the unknown resistance D is calculated from the proportion:

$$\frac{\text{resistance B}}{\text{length A}} = \frac{\text{resistance D}}{\text{length C}} \quad . \quad . \quad . \quad . \quad (87).$$

or

$$D = \frac{B \times C}{A}.$$

The lengths of A and C are used instead of actual resistances as with the lozenge form of bridge, since the resistance is pro-

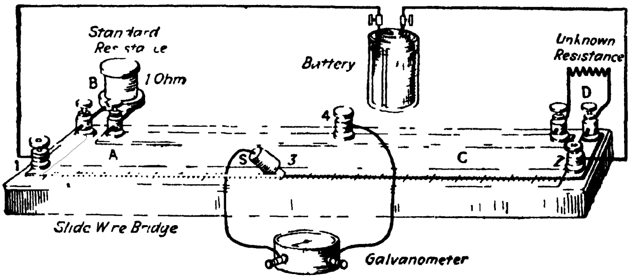


Fig. 230. — Student's Slide-wire Bridge.

Complete connections for measuring an unknown resistance are depicted

portional to the length. It will be observed that the last equation is identical with Formula (86).

Several different spools are furnished with the bridge, such as 1, 10, 100 and 1000 ohms, and the proper spool to be inserted at gap B should be as near in value to the resistance to be measured as can be approximated before measurement. The error in measurement is less when this is the case.

In moving the slider over the bridge wire care should be exercised not to scrape the wire, since the accuracy of measurement depends upon the uniformity of cross-section of the bridge wire. It is best to make several trial contacts at different points and note the direction of the needle's deflection, instead of running the slider along the wire. About the same pressure of the hand should be applied in making contact with the slider in different measurements. The slide wire form of Wheatstone bridge is adapted for measuring low resistances;

it is not as accurate, however, as the other forms, due to the wearing of the slide wire and its comparatively low resistance.

Problem 107. — The resistance of a spool of wire approximated as 20 ohms is connected to a slide-wire bridge for measurement, a 10-ohm spool is selected for the B arm of the bridge and the following data is recorded when balance is obtained: A = 350 scale divisions read from the left-hand zero mark, C = 650 divisions read from right-hand zero mark. What is the value of the unknown resistance?

By Formula (87) $D = \frac{B \times C}{A} = \frac{10 \times 650}{350} = 18.57$ ohms.

Problem 108. — What is the value of an unknown resistance measured by the slide-wire bridge when B = 1 ohm, A = 900 divisions, and C = 100 divisions.

By Formula (87) $D = \frac{B \times C}{A} = \frac{1 \times 100}{900} = 0.11$ ohm.

234. Commercial Wheatstone Bridges and Portable Testing Sets. — In practice the commercial form of Wheatstone bridge is seldom made in the lozenge shape illustrated in Figs. 226 and 227, for that is merely a laboratory form used in teaching the principles involved. The commercial forms of Wheatstone bridge or "portable testing sets" as they are sometimes called, consist of the bridge and rheostat arms mounted in a box usually with a galvanometer, a battery and two keys. With these portable testing sets resistances varying from a fraction of an ohm to millions of ohms can be measured.

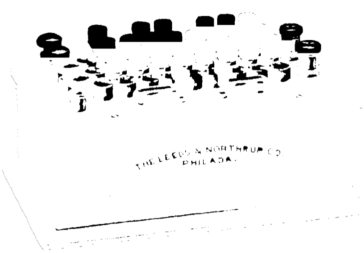


Fig. 231. — "Post-Office" Pattern of Wheatstone Bridge.

Post-Office Bridge. — One of the older forms of portable testing sets, the "Post-Office" pattern of Wheatstone bridge, is shown in Fig. 231. It consists of an arrangement of coils and brass blocks forming three arms of the Wheatstone bridge, resistance coils being inserted in the circuit by removing tapered plugs from the tapered holes formed between adjacent blocks, as in the plug type of rheostat shown in Fig. 67. This testing

set requires a separate battery and galvanometer, whereas in most portable testing sets the battery and galvanometer are also contained within the case.

The general plan of the "Post-Office" form of bridge and its connections are shown in Fig. 232, in which the letters and figures correspond to similar parts in the diagrams of the lozenge form of bridge (Figs. 226 and 227) so that the lozenge may be traced out, though the parts are not arranged in the form of a lozenge. The current from the battery divides at point 1 and unites again at point 2, and the galvanometer is connected across points 3 and 4 as in Fig. 227. Both the A and B arms are provided with four different resistances each, only one being used in each arm at any one time. The method of operating this bridge and the selection of resistance values of the A and B arms are as given in ¶ 232. For measuring low and medium resistances one or two cells in series may suffice to operate the bridge. The higher the E. M. F. used the more accurate will be the results. For very high resistances, such as insulation resistance, a large number of cells is employed.

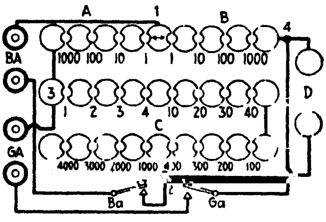


Fig. 232. — Connections of "Post-Office" Bridge.

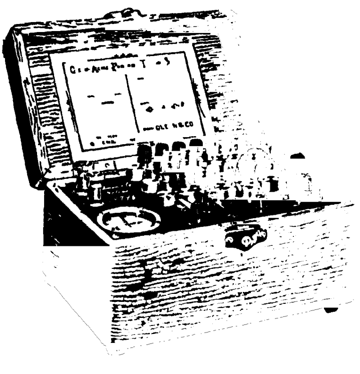


Fig. 233. — Self-contained Bridge or Portable Testing Set.

Queen-Acme Bridge.— An early commercial form of portable testing set, containing the battery and galvanometer within the case, is shown in Fig. 233, and is known as the Queen-Acme testing set. There are three rows of blocks, the center row constitutes the bridge arms and the outer rows, joined together

by a copper bar connecting the right-hand blocks, constitute the rheostat, whose resistance can be varied from 1 ohm to 11,110 ohms by removing the proper plugs. In the simplified diagram of the connections and circuits of the Queen-Acme testing set (Fig. 234) the blocks A, B, R and X form a commutator, the function of which is merely to transpose the two bridge arms A and B for various measurements by means of two tapered plugs.

To make a resistance measurement with this set, the unknown resistance is connected to the large binding posts at the left-hand side of the instrument and the + terminal of the battery connected to the battery post marked +, set the commutator plugs according to arrow H (or arrow L) as indicated on top of the set. If the unknown resistance is thought to be higher than 6100 ohms, set the commutator plugs in the direction indicated by arrow H; if the unknown resistance is lower than 1100 ohms, follow the direction indicated by arrow L, Fig. 234; and if the unknown resistance is between 1100 and 6100 ohms the commutator plugs could be set to follow either arrows H or L. In selecting the resistance values of the A and B arms for this testing set, the value of A should be equal to or smaller than B. Having set the commutator plugs and inserted the proper resistance values in the A and B arms, remove plugs from the rheostat until the aggregate resistance unplugged is equivalent, as nearly as may be approximated, to the unknown resistance. Depress the battery key and, holding that down, momentarily press the galvanometer key. If the galvanometer needle swings toward the side of the scale marked with a + sign, the resistance unplugged in the rheostat is too high and should be reduced. If the deflection is toward the − side, the resistance in the rheostat is too low and should be increased; the resistance in the rheostat being adjusted in this way until a balance is obtained.

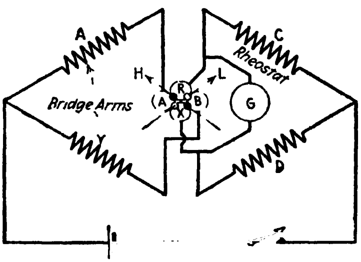


Fig. 234. — Scheme of Queen-Acme Bridge.

If the commutator plugs have the position of arrow L, then the unknown resistance $D = \frac{A}{B} \times C$, where C = value of resistance in the rheostat; if plugs have the position of arrow H, then $D = \frac{B}{A} \times C$.

Decade Portable Testing Sets. — In the *decade* form of testing set, the resistance coils that constitute the rheostat part of the set are arranged in equal series groups of nine or 10 coils in series in each group; that is, there are nine or ten 1-ohm coils for units place, nine or ten 10-ohm coils for the tens place, nine or ten 100-ohm coils for the hundreds place, and so on; each group of coils of the same value is designated a *decade*. In this form of bridge, resistance is inserted in the circuit by placing a *plug in the hole* instead of removing the plug.

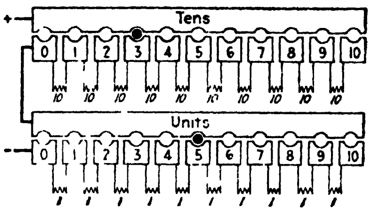


Fig. 235. — Connection of 10-coil Decades.

The coils are connected in series through small brass blocks that face one long brass bar as illustrated in Fig. 235, and the resistance value in any one decade is obtained by inserting between the bar and a block, one, and only one, plug. With several decades in series any value up to the limit of the set can be read off directly from the position of the plugs, without any addition whatever. Thus, in Fig. 235 the resistance between the + and − terminals for the two decades is 35 ohms. This decade arrangement avoids the disadvantage of the previously-described bridges in that the latter requires a large number of plugs to short circuit the resistance coils not in use (which introduces an element of uncertainty as to the resistance of the plug contacts) and necessitates adding up the values of all the unplugged resistances in order to determine the total resistance in the circuit.

An improved form of decade testing set, devised by the Leeds

& Northrup Co. and used in some of the sets manufactured by them, combines the advantages of the above form of decade arrangement with the need of but few coils. In these sets four coils are in series in each decade instead of nine: — in the units decade there are two 3-ohm coils in series with a 2-ohm and a 1-ohm coil, making a total of 9 ohms; in the tens decade there are one 10-ohm, one 20-ohm and two 30-ohm coils; and so on. The method of connecting these coils in a decade so as to obtain any value within the range of that decade is shown in Fig. 236, the circles in the diagram representing two rows of ten brass blocks each. If a plug is inserted between the first two blocks at the top of the rows the resistance value would be 0, if the plug is inserted between the blocks in the second horizontal line 1 ohm is obtained, if the blocks in the third horizontal line be connected 2 ohms, and so on; the total resistance of 9 ohms being obtained when the plug is in the ninth or last pair of blocks, which have no connections. The coils in each decade are connected in this manner and the decades connected in series so that the total range in, say, four decades, is 9999 ohms, obtainable in one-ohm steps.

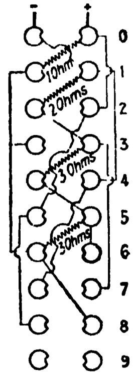
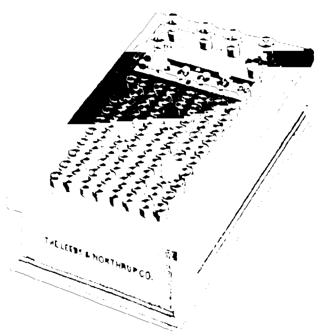


Fig. 236. — Connection of 4-coil Decades.

A plug-type decade pattern of Wheatstone bridge, using four coils in a decade as described above, is shown in Fig. 237; in these sets a special arrangement of the resistance coils forming the ratio arms A and B of the bridge is such as to require only one plug in each arm, instead of three, as in the "Post-Office" bridge and the Queen-Acme testing sets. In the plug decade set (Fig. 237) each of the six ratio coils has one of its terminals


Fig. 237. — Leeds and Northrup Decade Bridge.

connected to a common center which leads to the galvanometer, while the other terminal of each coil is connected to an individual block, there being one block for each coil. The bar B on one side of these blocks is joined to the rheostat and the bar A on the other side to one of the posts marked "X" where the unknown resistance is connected. To insert a resistance in the A arm, a plug is inserted between bar A and one of the central row of blocks that will give the desired resistance value; a plug inserted between bar B and one of the other blocks in the center row will insert a resistance coil in the B arm. With the set shown in Fig. 237 a separate battery and galvanometer are used; when these are connected to the posts marked Ba and Ga respectively and the unknown resistance is joined to posts X, the regular Wheatstone bridge circuits are formed. This set may also be used as a rheostat alone when connections are made to the two posts at the upper right-hand corner of the set.



Fig. 238.—Leeds and Northrup Decade Testing Set.

A plug decade portable testing set containing a battery, galvanometer and the necessary keys, in addition to the plug decade rheostat and ratio coils as described above, is shown in Fig. 238.



Fig. 239.—Dial Type Wheatstone Bridge or Testing Set.

A form of portable testing set that is rapidly replacing the plug decade set is the "Dial" decade set (Fig. 239) because the dial control of resistances is quicker and more convenient than the plug control. In this set there is a dial type Wheatstone bridge, consisting of ratio arms and a four-dial decade-type rheostat. a galvanometer, a battery and two keys. The two

ratio coils are controlled by one dial, which arrangement adds materially to the convenience of the operator for it determines at once the value by which the rheostat reading should be multiplied. The multiplying values are stamped on the ratio dial, and are 0.001, 0.01, 0.1, 1, 10, 100, 1000, giving the usual ratio range. With this form of bridge a balance may be obtained very quickly.

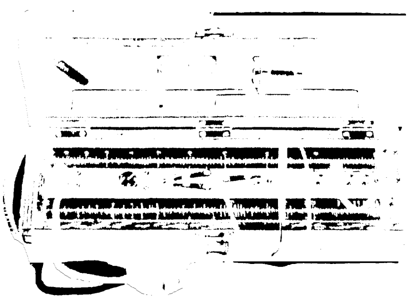


Fig 240 — Roller-Smith Ohmmeter (Combined Telephone and Galvanometer Type). Operates like a slide-wire bridge.

235. Ohmmeters. — Instruments for the direct measurement of resistance, called ohmmeters, are of two general types. One type operates on the principle of the slide-wire bridge (that is, potentials are balanced), the balanced condition being indicated by a galvanometer or a telephone receiver. The scale under the slide wire is laid off in ohms (or in per cent of a fixed resistance value) so that the value of the resistance being measured is read directly in ohms. Fig. 240 shows a slide-wire ohmmeter of this type suitable for locating line breaks, grounds and crosses, for measuring resistance of electrolytes, etc. The principle of operation of this instrument is the same as that of the slide-wire bridge (¶ 233).

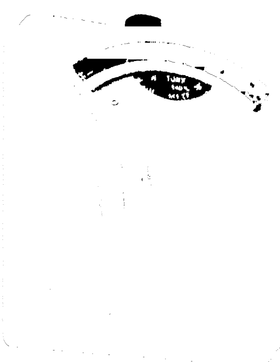


Fig. 241. — Weston Ohmmeter.

The second type measures the resistance automatically by means of a movable coil which carries a pointer sweeping over a scale graduated in ohms, so that the value of the resistance connected to the instrument is read directly from the scale,

no calculations being required. The Weston direct-reading ohmmeter, of which an external view is shown in Fig. 241 and its construction and circuits in Fig. 242, is an instrument belonging to the second type above mentioned. In mechanical construction, the instrument is practically the same as the Weston D. C. voltmeter or ammeter, that is, it contains a

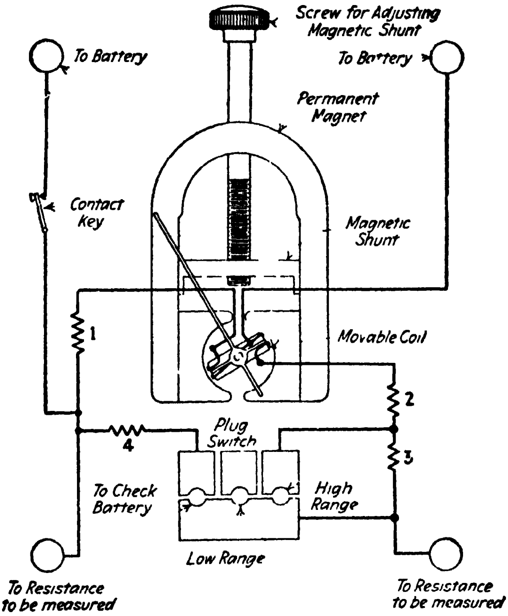


Fig 242. — Construction and Circuits of the Weston Ohmmeter.

horseshoe permanent magnet, provided with soft iron pole pieces between which is pivoted the movable coil carrying the pointer. The winding of the movable coil is divided into two parts by means of a tap at the center of the winding, and these two parts are included one in each of two branch circuits, the deflection of the movable coil depending upon the currents flowing through the parts of its winding, which currents are proportional to the resistances connected to the branch circuits. By

tracing the flow of current from the upper right-hand battery post of Fig. 242 it will be found that the current entering the coil at the top will divide and flow through the parts of the coil winding in opposite directions, a part of the total current flowing through resistance 1 and back to the battery, and the other portion of the current flowing through resistances 2 and 3 (if the plug is in the low-range block of the plug switch) and through the unknown resistance back to the battery. Fig. 243 shows the same connections more clearly, all construction details being omitted. It will be seen, herefrom that the current through the upper portion of the movable coil winding and resistance 1 will remain the same; whereas the current through the lower portion of the coil winding, resistances 2 and 3, and the unknown resistance X in series, will depend upon the value of the unknown resistance.

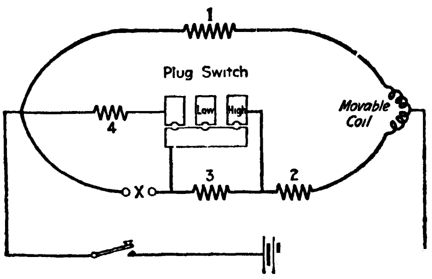


Fig. 243. — Electrical Scheme of the Weston Ohmmeter.

The current in the upper half of the divided circuit (Fig. 243) will remain the same under a constant E. M. F., and the direction of this current in the coil is such as to move it in a direction to sweep the pointer across the scale. The current in the other portion of the movable coil is in the opposite direction and consequently opposes the motion of the coil, its motion is then the resultant of the two magnetic forces produced in the two parts of the coil. With an unknown resistance of a high value connected to the instrument the current in the lower half of the movable coil would be weak, and the magnetic force of the other half of the coil would practically be unopposed, thus producing a large deflection. If the unknown resistance is low then the opposite effect is produced, since the current and resulting magnetic force in that half of the movable coil which is in series with the unknown resistance will be increased, thus setting up a greater opposing force.

Resistances 1, 2 and 3 in Figs. 242 and 243 are so proportioned that the resultant ampere-turns on the coil are zero when the unknown resistance X is zero. Resistance 4 has a value in ohms equal to the full-scale value of the instrument and may be connected in the circuit by means of the plug switch, i's function being to check the instrument at its top mark at any time. If, due to changes in the battery E. M. F., the top mark indication is not exactly correct, it may be made so by adjusting the self-contained *magnetic* shunt (Fig. 242) by turning the thumb screw at the top of the instrument.

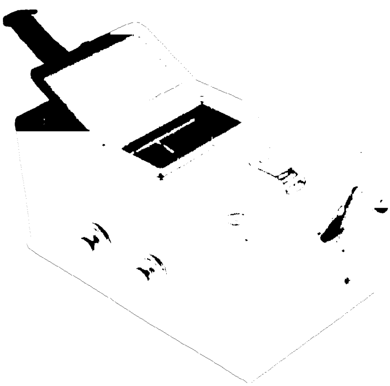


Fig. 244. — "Megger" Testing Set.
For measuring high resistances.

Weston ohmmeters are made with double ranges, the plug switch serving to make the change from one range to the other. The instruments may be operated with ordinary dry cells, four cells for the high-range and two cells for the low-range instruments. To measure a resistance with this instrument, connect a battery to the proper binding posts and the unknown resistance to the two binding posts provided for the purpose, press the contact key and read the value of the unknown resistance in ohms directly from the scale.

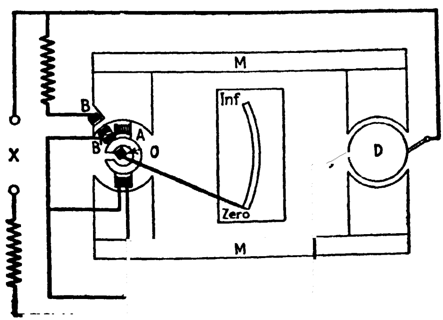


Fig. 245. — Magnetic Circuit and Electrical Connections of "Megger" Testing Set.

An instrument that will measure higher resistances than the Weston ohmmeter is the instrument sold under the trade-name of "Megger," by James G. Biddle of Philadelphia, Pa The "Megger" testing set consists of a direct-reading ohmmeter and a hand-driven direct-current generator assembled in a portable box (Fig. 244). An understanding of the operation of the set can be obtained by considering Fig. 245, which shows the essentials of the magnetic circuit and of the electrical connections. Herein MM are two permanent bar magnets, between the poles of which at one end is the armature D of the generator, while at the other end is the moving indicating system of the ohmmeter. This system is made up of three coils, A, B and B′ rigidly fixed together, and freely rotating about the axis O, without the directive influence of any controlling springs. The details of construction of the movable element are illustrated in Fig. 246.

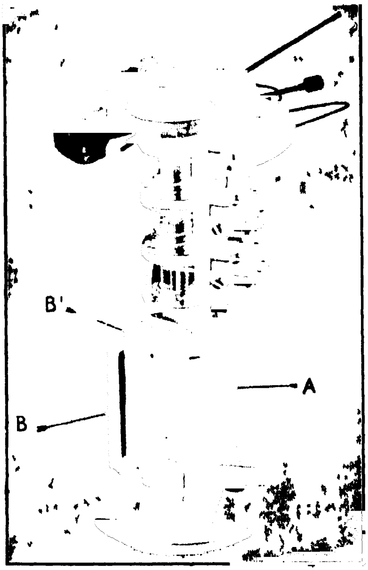


Fig 246. — Moving System of the "Megger."

If nothing is connected across the external terminals, and the generator is operated at proper speed by the small crank at the right-hand end of the set, as shown in Fig. 244, current from the generator will flow only through the two coils B and B′ connected in series (Fig. 245). The electrical reaction thus set up drives these coils to a position where minimum flux from the permanent magnets passes through them; that is, directly opposite the gap in the C-shaped iron piece about which the coils A and B′ move. The pointer then stands

over the line on the scale marked "Infinity," at the extreme upper end of the scale. Now, if a suitably high resistance is connected to the external terminals, the current from the generator has two paths open to it and will divide, part passing through coils B and B′ as before, and part through coil A which is in series with the resistance under test. The current in coil A exerts a deflecting torque toward the position shown in Fig. 245, and opposes that produced by coils B and B′. As the system moves, the coils B and B′ offer an increasingly strong restraining torque until the turning force due to coil A is balanced and the needle comes to rest at a point on the calibrated scale which correctly indicates the value of the resistance connected between the external terminals. Should these terminals become short-circuited no harm is done to the instrument; the coil A simply overpowers coils B and B′ and the pointer is moved to the lowest point on the scale, marked zero. Both circuits in the instrument have suitable series resistances, as indicated in Fig. 245, for the purpose of properly protecting the sensitive parts from unduly large currents. The voltage produced by the generator in these instruments varies from 100 to 1000 volts direct current, depending upon the range of the instruments. "Megger" testing sets are adapted to a wide range of measurements, such as testing the insulation resistance of motors and generators, of house wiring, and of power and telephone cables, measuring resistance of conductors, etc.

QUESTIONS

1. How would you measure the resistance of an incandescent lamp while illuminated? Give a sketch.
2. By what method would you measure the cold resistance of the lamp in Question 1?
3. How would you measure the resistance of a coil of wire using a voltmeter of known resistance and a source of electric pressure? Give a sketch.
4. With a voltmeter only, and a source of E. M. F., how would you measure the insulation resistance of the field windings of a generator? Give a sketch.
5. What is the fundamental principle of the Wheatstone bridge? Give a sketch.

6. The highest and lowest resistances available in the rheostat of a Wheatstone bridge are 10,000 ohms and 0.1 ohm respectively. The A and B arms have each 1-, 10-, and 100-ohm coils. What are the highest and lowest resistances that the bridge is capable of measuring?

7. In making a resistance measurement with a Wheatstone bridge, how would you know when too much, or too little, resistance has been inserted in the rheostat?

8. Explain what is meant by a "decade" as applied to resistance boxes.

9. What is the advantage of the decade testing sets over the old type testing sets such as the Post-Office bridge?

10. What are the two general types of ohmmeters? Explain the operating principle of each.

11. Describe the operation of the "Megger."

PROBLEMS

1. The drop across the series field coil of a dynamo carrying 250 amperes is 0.7 volt. What is its resistance? *Ans.* 0.0028 ohm.

2. A rheostat, battery, galvanometer and unknown resistance are joined in series. With 40 ohms unplugged in the rheostat the galvanometer deflection is 33. The unknown resistance is cut out of circuit and 45 additional ohms are inserted to reduce the deflection to its former value. What is the value of the unknown resistance? Give a sketch. *Ans.* 45 ohms.

3. You are required to measure the insulation resistance of an electromagnet using a proportionate deflection galvanometer whose sensibility is 0.00001 ampere per division. Using a 250-volt supply circuit on the electromagnet causes the needle of the galvanometer to be deflected 3 divisions. What is the insulation resistance? Give a sketch. *Ans.* 8,333,333 ohms or 8.3 megohms.

4. The field magnets of a dynamo having a resistance of 84 ohms are connected in series with the field magnets of another machine, and a current is sent through the circuit. The drop on the latter field coils is 111 volts, and on the 84-ohm coils is 37 volts. What is the resistance of the second set of field magnets? *Ans.* 252 ohms.

5. Balance is obtained in a Wheatstone bridge when A = 10 ohms, B = 100 ohms, and rheostat = 14 ohms. What is the value of the unknown resistance? Give a sketch. *Ans.* 140 ohms.

6. Using a 10-ohm standard resistance with a slide-wire bridge having a wire 10 inches long, specify the calibration of the wire so as to indicate directly by the position of the slider the resistance of an unknown.

LESSON XX

ELECTRICAL DEVELOPMENT OF HEAT

Heating of Conductors and Their Safe Current-carrying Capacity — Table XIII — Electrical Development of Heat — Electrical Equivalent of Heat — Relation Between Heat, Mechanical and Electrical Energy — Relation Between Fahrenheit and Centigrade Thermometer Scales — Dependence of Resistance upon Temperature — Table XIV — Fuses — Electric Welding — Electric Cautery, Blasting, Heating and Cooking — Measurement of Temperature by Resistance Change; Pyrometry — Thermo-electric Pyrometers — Table XV — Questions and Problems.

236. Heating of Conductors and Their Safe Current-carrying Capacity.—Heat is evolved when the molecules of a body are set in motion. To produce this motion requires the expenditure of a definite amount of mechanical energy. When a current of electricity passes through a wire, a certain amount of work is performed in overcoming the resistance of the wire, and this work appears as heat, the amount generated agreeing with the principle of conservation of energy (¶ 141). This heating effect becomes very noticeable when the wire is small and the current large; the wire may then become so hot that it is melted by the current. The increase in the temperature of a wire, due to the current, depends upon its weight or sectional area. For example, two copper wires, one weighing one pound, and the other twice as long but weighing four pounds, offer *equal resistance* to a given current passed through them, but the wires will not be raised to the same temperature, although the amount of heat evolved in both cases is exactly the same. This is true because there is more metal to heat in one case than in the other. Thin wires, therefore, heat much more rapidly than thick ones of a like resistance when traversed by the same current. Since the resistance of metals increases as their temperature rises, a wire will have its resistance increased as it becomes heated, and will continue to grow warmer until its rate of loss of heat by conduc-

tion, convection and radiation to the surrounding air or other objects equals the rate at which the heat is evolved by the current

Experiment 80. – When a chain made of alternate links of platinum and silver wire of the same size, is connected to several cells joined in series, the platinum links become red-hot but the silver links remain comparatively cool. The resistance of platinum is about 6 times as great as silver, but its capacity to absorb heat only about one-half as great, hence its rise in temperature is about twelve times as great as that of the silver for the same current.

The heating of a wire by a current is not objectionable except that it increases the loss of energy by the rise in resistance The real limit of the current-carrying capacity of a wire is at such a rise of temperature that the insulation is liable to be damaged. The safe current-carrying capacities prescribed by the National Electrical Code of the Fire Underwriters for copper wires are given in Table XIII. The values are for rubber-covered and varnished cloth-covered wires and for wires having a covering of some other material. It will be noted that the latter wires are permitted to carry more current since the insulation covering the wires is not as readily affected by the heat as the first mentioned.

Table XIII. Current-carrying Capacity of Copper Wires

B. & S. Gage Wire	Rubber Insulation, Amperes	Varnished Cloth Insulation, Amperes	Other Insulation, Amperes
18	3		5
16	6	—	10
14	15	18	20
12	20	25	25
10	25	30	30
8	35	40	50
6	50	60	70
5	55	65	80
4	70	85	90
3	80	95	100
2	90	110	125
1	100	120	150
0	125	150	200
00	150	180	225
000	175	210	275
0000	225	270	325

The carrying capacity of copper wires used in dynamos varies from 500 to 1000 circular mils per ampere, according to the amount of ventilation the wire may receive. A much larger allowance must be made for contact surfaces in a circuit, as between the brushes of a dynamo and the commutator, the clips of a switch, etc.; about 100 amperes per square inch of contact surface is an average value. Switches are constructed and rated according to their current-carrying capacities.

237. Electrical Development of Heat. - When an electric current flows through a conductor a certain amount of electrical energy is transformed into *heat* energy. This fact may be very forcibly illustrated if the current the wire is carrying is great enough to heat it to incandescence. The actual amount of heat developed in any case is the exact equivalent of the amount of electrical energy expended in overcoming the resistance of the conductor. The amount of heat developed varies directly with the resistance of the wire, the square of the current, and to the time during which the current flows; therefore, if H represents the number of heat units developed, I the current in amperes, R the resistance in ohms, and t the time in seconds, then the development of heat in an electric circuit is given by the following equation:

$$H = I^2 \times R \times t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (88).$$

where the amount of heat, H, is expressed in joules or watt-seconds. These facts were first ascertained by Dr. Joule, and the foregoing equation is known as Joule's Law.

This law may be illustrated as follows: (1) suppose we have two equal resistances, A and B, and that twice the P. D. is maintained across A that is applied to B, then the heating effect in A will be quadruple that in B, since with equal resistances the current strength will be doubled in A and energy is expended four times as fast in A as it is in B. (2) If the resistance of B is increased to twice that of A and the same P. D. is maintained across both, then the current in B will equal one-half that in A. Hence, if in A, $H = I^2R$, then in B, $H = (\frac{1}{2}I)^2 \times 2R = \frac{1}{2}I^2R$, and consequently twice as much heat is developed and twice as much energy expended in A as compared with B. (3) If the current in B is then made

equal to that in A, by doubling the P. D. across B, then in A, H = E × I or I^2R and in B, H = 2 E × I, or 2 I^2R, so that doubling the resistance and keeping the current constant doubles the heat developed and causes twice the amount of energy to be expended.

238. Electrical Equivalent of Heat.— The amount of heat liberated by an electric current may be measured by passing the current through a known resistance immersed in a known weight of water. This is usually done with a device called a calorimeter (Fig. 247), which is a vessel containing the water in which the resistance, a coil of platinoid or German silver wire, is immersed. The vessel is usually double-walled or arranged in some way so that it will lose little heat by radiation into the air. A thermometer is immersed in the liquid to determine its rise of temperature due to the heat given to it from the wire. The quantity of heat evolved is the product of the mass of water and its temperature elevation.

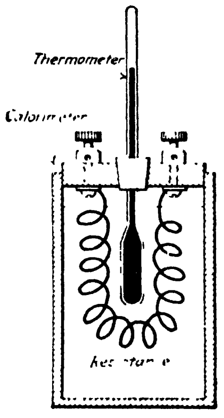


Fig. 247. - Calorimeter.

From a calorimeter experiment made by Dr. Joule, to determine the heat equivalent of electricity, he found that one ampere flowing through one ohm for one second always developed 0.24 of a *calorie* of heat — a calorie being the amount of heat required to raise the temperature of one gram of water one degree Centigrade. Therefore, 1 joule of energy is equivalent to 0.24 calorie of heat or 1 calorie is equivalent to $\frac{1}{0.24} = 4.2$ joules. These numerical values are known as *Joule's coefficient* or the *electrical* (or mechanical) *equivalent of heat.* These values are used when the weight of water is measured in grams and the temperature rise is taken with a Centigrade thermometer (¶ 240).

TO FIND THE AMOUNT OF HEAT DEVELOPED IN A CONDUCTOR IN CALORIES:

Multiply 0.24 *times the resistance of the conductor by the square of the current and by the time (in seconds) that the current flows,* as is given by Joule's Law:

$$H = 0.24 \times I^2 \times R \times t \qquad (89).$$

The British Thermal Unit of heat (abbreviation B. T. U.) is the amount of heat required to raise one pound of water one degree Fahrenheit. Since one ampere flowing for one second through one ohm resistance is found to develop 0.000948 of a B. T. U., this value 0.000948 is the heat equivalent used if the weight of water is expressed in pounds and the rise in temperature is noted with a Fahrenheit thermometer.

TO FIND THE AMOUNT OF HEAT, EXPRESSED IN B. T. U., THAT WOULD BE DEVELOPED IN A GIVEN TIME BY THE EXPENDITURE OF ELECTRICAL ENERGY IN A CIRCUIT:

Multiply the watts expended by the time (in seconds) that the current flows and this product by 0.000948, as in following formula:

$$H = 0.000948 \times E \times I \times t, \qquad (90).$$

or

$$H = 0.000948 \times I^2 \times R \times t. \qquad (91).$$

When it is desired to determine the amount of heat that would raise a quantity of water to a certain temperature from an initial temperature, multiply the weight of water by the degrees rise. If the heat is to be expressed in calories then H = grams × degrees Centigrade, and if in B. T. U. then H = pounds × degrees Fahrenheit.

Problem 109. — How many heat units are evolved in one-half hour (1800 seconds) by a 110-volt incandescent lamp taking a current of ½ ampere?
By Formula (90) $H = 0.000948 \times 110 \times 0.5 \times 1800 = 93.82$ B. T. U.

TO FIND THE CURRENT REQUIRED TO PRODUCE ANY GIVEN NUMBER OF B. T. U. BY A KNOWN E. M. F. IN A GIVEN TIME USE THE FORMULA:

$$I = \frac{H}{0.000948 \times E \times t} \qquad (92).$$

TO FIND THE TIME REQUIRED TO PRODUCE A GIVEN NUMBER OF B. T. U. BY THE EXPENDITURE OF A GIVEN AMOUNT OF ENERGY USE:

$$t = \frac{H}{0.000948 \times E \times I} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (93).$$

These equations result from equation (90) by transposition

Problem 110. A 110-volt, ½-ampere incandescent lamp is immersed in a vessel containing 1 pound of water. How long a time will be required to raise the water to the boiling point? The temperature of the water before the test is 60° F. Neglect the losses due to radiation, etc., and assume that all the energy is converted into heat.

The water must be raised 212° − 60° = 152° F.

The heat units to be given to the water = 1 lb. × 152° = 152 B. T. U.

By Formula (93) $t = \frac{152}{0.000948 \times 110 \times 0.5} = 2916$ seconds,

or $\frac{2916}{60} = 48$ minutes and 36 seconds.

Problem 111. — What current will be required by a lamp immersed in the above pound of water to boil it in one-half hour? The E. M. F. is 110 volts and the heat losses are to be neglected.

Solve by Formula (92). *Ans.* 0.81 ampere.

239. Relation Between Heat, Mechanical and Electrical Energy. — Referring to ¶ 142, Formula (52), etc., we find that the electrical work performed in a circuit is proportional to the same factors as the heat development, Formulæ (88) to (90). This is necessarily true, since the electrical work expended appears as heat. The following problem will illustrate the relation between electrical work, in joules, and the heat, in calories or B. T. U.

Problem 112. — A current of 4 amperes flows through 2 ohms for 30 seconds. (a) Find the work performed in joules. (b) Find the number of heat units developed in the circuit.

By Formula (52) $J = I^2 \times R \times t = 4 \times 4 \times 2 \times 30 = 960$ joules,
By Formula (89) $H = 0.24\ I^2 \times R \times t = 0.24 \times 960 = 231$ calories,
By Formula (91) $H = 0.000948\ I^2 \times R \times t = 0.000948 \times 960 = 0.910$ B. T. U.

The relation between mechanical energy, electrical energy and heat energy (¶ 145) *is then summarized as follows:*

MECHANICAL ENERGY		ELECTRICAL ENERGY		HEAT ENERGY		
778 foot-pounds	=	1055 joules	=	252 calories =	1	B. T. U.
3.09 "		4.2 "		1 calorie	0.00397	"
0.737 "		1 joule		0.24 "	0.000948	"

240. Relation between Fahrenheit and Centigrade Thermometer Scales. — Since both the Fahrenheit and Centigrade thermometric scales are much used in referring to the resistance of a wire at a particular temperature, the relation between them is given by the formulæ below, and also shown diagramatically by Fig. 248. On the Fahrenheit scale the melting point of ice is placed at 32° and the boiling point at 212°, while on the Centigrade scale the melting point of ice is placed at zero and the boiling point at 100°. Therefore, 100 Centigrade degrees = 212 − 32 = 180 Fahrenheit degrees, or the ratio of a degree Centigrade to a degree Fahrenheit is as 9 is to 5. In converting a Centigrade reading into a Fahrenheit reading 32 must be added after multiplying by $\frac{9}{5}$, and conversely 32 must be subtracted from a Fahrenheit reading before multiplying by $\frac{5}{9}$.

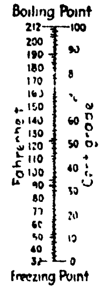


Fig. 248. — Comparison of Fahrenheit and Centigrade Thermometer Scales.

To convert a reading from the Fahrenheit to the Centigrade scale:

Subtract 32, multiply by 5 and divide by 9.

$$C^\circ = \frac{(F^\circ - 32)5}{9} \quad \ldots\ldots \quad (94).$$

To convert a reading from the Centigrade to the Fahrenheit scale:

Multiply by 9, divide by 5 and add 32.

$$F^\circ = \frac{C^\circ \times 9}{5} + 32 \quad \ldots\ldots \quad (95).$$

Problem 113. — A field-magnet spool is said to have a resistance of 25 ohms at 15.5° C. Express this temperature in degrees Fahrenheit.

By Formula (95) $F^\circ = \frac{C^\circ \times 9}{5} + 32 = \frac{15.5 \times 9}{5} + 32 = 59.9$, or nearly 60° F.

Problem 114. — The temperature of a certain type of insulation should not exceed 180° F. What is the corresponding temperature on the Centigrade scale?

By Formula (94) $C^\circ = \frac{(F^\circ - 32)\,5}{9} = \frac{(180 - 32) \times 5}{9} = 82.2^\circ$ C.

241. Dependence of Resistance Upon Temperature. — As indicated in ¶ 67 on the Laws of Resistance, the resistance of all pure metals increases with rising temperature. The *proportional* change in resistance of a wire with a unit change in temperature is known as the *temperature coefficient,* or it is the amount in ohms that the resistance increases per ohm, for each degree rise in temperature.

The temperature coefficients for the different metals are determined experimentally and their value depends upon what temperature is taken as the standard or initial temperature. Representing the initial temperature by t, the temperature coefficient of resistance of copper on the Centigrade scale is given by the equation $a = \frac{1}{234.5 + t}$; consequently for an initial temperature of 0° Centigrade, the resistance of copper increases $\frac{1}{234.5 + 0} = 0.00427$ ohm per degree for each ohm at 0° C. For example, if the resistance of a copper wire is 10 ohms at 0° C., for a rise of 1° C. it would have a resistance of $10 + (10 \times 0.00427)$ or 10.0427 ohms, and at a temperature of 20° C. it would have a resistance of $10 + (10 \times 20 \times 0.00427) = 10.854$ ohms.

The average temperature coefficient between 0° and 100° C., and 32° and 212° F. for all pure metals is roughly the same. and is about 0.004 per degree Centigrade and 0.0023 per degree Fahrenheit.

This change in the resistance of a wire due to the temperature rise or fall is a very important matter in electrical calculations and measurements, and must always be taken into consideration. The following formulæ and temperature coefficients, Table XIV, will enable the student to calculate the resistance of different metals at different temperatures:

Let R = resistance of a conductor at the initial temperature,
R_1 = resistance after a rise or fall in temperature,
T = number of degrees rise or fall,
a = the temperature coefficient, or the change of resistance per degree per ohm.

The formula for finding the increase in resistance due to a rise in temperature is:

$$R_1 = R\,[1 + (a \times T)] \quad \ldots\ldots\ldots\ldots \quad (96).$$

For a drop in temperature T is taken negative, or the equation may be written

$$R_1 = R\,[1 - (a \times T)].$$

When the Centigrade scale is used select the temperature coefficient (a) for this scale and similarly for the Fahrenheit scale. The following temperature coefficients (values of a) for some metals represent accepted values for an initial temperature of 68° F. or 20° C., unless otherwise stated. The figures give the amount 1 ohm would increase or decrease in resistance when subjected to a rise or fall of one degree F. or C.

Table XIV. Temperature Coefficients of Resistance

Metal	Fahrenheit Scale (at 68° F.)	Centigrade Scale (at 20° C.)
Silver	0.00210	0.00377
Copper (annealed)	0.00218	0.00393
Aluminum	0.0022	0.0039
*Platinum	0.00204	0.00367
Iron	0.00293	0.00527
*Nickel	0.0035	0.0062
Lead	0.00215	0.00387
Nichrome	0.00024	0.00044
German silver (average)	0.00017	0.00031
Manganin	0.00001	0.00002

* Average value for range from 0° C. to 100° C.

Problem 115. — The resistance of the field magnets of a dynamo is 55 ohms at 70° F.; after a ten-hour run the temperature indicated by a thermometer placed against them is 160°. (a) What is their resistance at this temperature? (b) What would be the resistance at 32° F.?

Since 70° F. = 21.1° C., the temperature coefficient of copper to be used in this problem is $a = \frac{1}{234.5 + 21.1} = \frac{1}{255.6} = 0.00392$ for the Centigrade scale or $\frac{5}{9} \times 0.00392 = 0.00218$ for the Fahrenheit scale.

By Formula (96) for a temperature rise of $160 - 70 = 90°$ F.,

$$R_1 = R[1 + (a \times T)] = 55[1 + (0.00218 \times 90)] = 65.8 \text{ ohms (a)}.$$

The resistance of the magnets at 32° F would be $R_1 = 55[1 - (0.00218 \times 38)] = 50.4$ ohms (b).

242. Fuses.—When a piece of copper and a piece of lead wire of the same size are connected in series and a current of increasing strength passed through them, it will be observed that the lead will melt when a temperature of 615° F. is attained, while at that temperature copper will not melt. Lead containing a small percentage of tin will melt at a lower temperature than pure lead, and this alloy is used in electric fuses for the protection of the copper conductors. A fuse inserted in series with electric circuits for their protection consists of a wire or strip of lead-tin alloy of such a size that it will melt and automatically open the circuit when the current flowing in it exceeds a predetermined value. The carrying capacity of a fuse depends upon its cross section; thus commercial fuse wire $\frac{1}{10}$ inch in diameter will be melted by a current of 55 amperes.

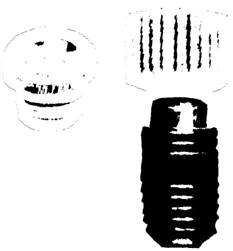


Fig. 249. - Plug Fuses.

A fuse is generally rated to be of so many amperes capacity, meaning that it will carry this current without melting or "blowing," as it is termed, and melt on a slight increase in current above its capacity. The function of a fuse, therefore, is to open the circuit before the temperature rise due to an excessive current from any cause, has opportunity to unduly heat the conductors. A circuit breaker (Fig. 146) performs the same function in a different way.

Fuses for the protection of electrical apparatus and circuits should melt at a definite current value and not be influenced by long heating; they should maintain good contact with the circuit by having hard metal end connections; they should be of sufficient length so that an arc will not be maintained when they melt, and should be so arranged that surrounding objects are not likely to be set on fire when they melt. Fuses

are connected in electric circuits at switch and panel-boards or at porcelain blocks provided with metal terminals for holding the fuse; the latter device is termed a cut-out, or fuse block. The early form of fuse was a lead-tin alloy wire or strip provided with copper terminals with which it was held in the fuse block; this was known as the *open-link fuse;* it was rather unsafe and unreliable. Modern fuses are completely enclosed in a container which is held in the fuse block. One form (Fig. 249), termed a *plug fuse*, has a screw thread on one end and is screwed into a plug type cut-out. The left-hand illustration shows a non-refillable plug fuse, while that at the right shows a modern renewable type. The latter has the advantage over the older type of plug fuse in that when the fuse melts the cartridge can be removed from the case and a new cartridge fuse inserted; these plug fuses are made for various currents up to 30 amperes.

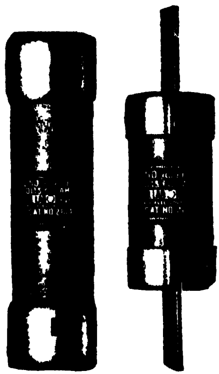


Fig. 250.—Ferrule Type Fuse. Knife Blade Type Fuse.

Cartridge or enclosed fuses consist of a fiber tube with a brass cap at each end; the fuse link of lead-tin alloy held inside of the cartridge reaches from one brass cap to the other, and is surrounded by an insulating powder. When the fuse "blows" some of the fuse metal is melted and vaporized and an arc tends to form across the gap; the powder cools and condenses the vapor so that the gap is rendered nonconducting, and the arc is quickly extinguished. For cartridge fuses up to 60 amperes, shown at the left of Fig. 250, contact is made with the circuit by clips which grip the end caps, and for larger sizes, the knife blade contact is used, shown at the right in Fig. 250. Most cartridge fuses are equipped with some sort of indicator so that upon external inspection one can determine if the fuse is in good condition or has been blown. Several manufacturers make enclosed fuses which permit of the renewal of the fusible element, thus enabling the cost of fuse maintenance to be materially lessened

243. Electric Welding. — Metals and alloys can be welded with the aid of the electric current, two distinct processes being employed, namely: the so-called *incandescent process*, and the *arc process*. The principle of the incandescent welding process, devised by Elihu Thomson, is that of causing a current of electricity to pass through the relatively high resistance presented at the junction of two metals, thereby generating heat. The two general methods of making an electric weld by the Thomson process are the *butt weld* and the *spot weld*. In the butt weld a current of electricity is passed through the abutting ends of the pieces of metal that are to be welded, thereby generating heat at the point of contact, which is also the point of greatest resistance, while at the same time mechanical pressure is applied to force the parts together. The passage of current through the metal at the point of junction gradually but quickly brings the temperature of the metal to the welding point, and the mechanical pressure applied simultaneously affects the weld. In the spot weld two or more metal sheets or parts are fused together electrically between two electrodes or welding points which are brought to bear on the plates where it is desired to make the weld. The metal parts to be welded are poor conductors of electricity relative to the electrodes and, therefore, offer so great a resistance to the flow of current that the metals heat almost to the molten state, and then, by applying pressure on the electrodes, the metals are forced together and the weld effected. The weld thus produced is mechanically equivalent to riveting, but it is stronger and can be done much more quickly and economically.

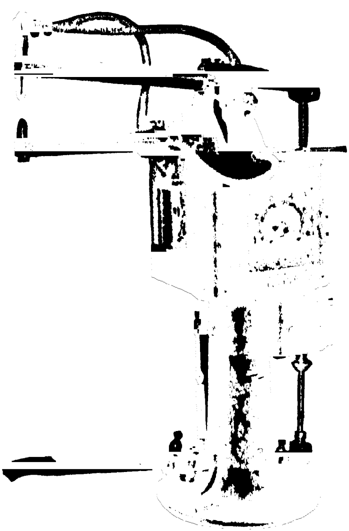


Fig. 251. — Winfield Spot-welder.

Welding machines for electrically welding metals are constructed in a variety of forms and are equipped with water-cooled electrodes and with transformers, ¶ 357. The transformer is made a part of the machine because alternating current is generally used, its function being to reduce the commercial voltages to a low value, since welds are made with heavy currents under a few volts pressure. Fig. 251 shows a spot-welder made by the Winfield Electric Welding Machine Company. The water-cooled electrodes are shown at the top of the machine, the upper one can be pressed against the lower stationary electrode by means of the foot treadle. The transformer is located in the perforated case in front of which is mounted the current regulator; this varies the current strength by altering the number of turns on the high-tension winding of the transformer.

In the arc process of electric welding the heat of the arc is utilized in bringing the metals to be welded to the proper temperature. The parts to be joined are connected to one terminal of the supply circuit and a welding pencil or rod of proper composition to the other terminal. Sometimes this pencil is not connected to the circuit and a carbon electrode takes its place. The welding pencil (diameter $\frac{1}{8}$ to $\frac{3}{16}$ inch) is melted by the arc and fills up the space purposely left between the pieces to be welded, this space being formed by beveling the edges of the welded parts either on one or on both sides. The arc process is much used in the welding of the mild steel plates of ship hulls. For plates from $\frac{1}{2}$ to 1 inch thick currents of from 150 to 400 amperes are usually used. The Welding Committee of the Emergency Fleet Corporation specified that the iron electrode wire for the welding of mild steel may have certain impurities to a percentage not in excess of the following values: carbon 0.18, manganese 0.55, phosphorus 0.05, sulphur 0.05 and silicon 0.08. Alternating as well as direct current may be used for metal arc welding. A representative rate of deposit for a good welder with "Quasi-Arc" electrodes is about 2 pounds per hour for $\frac{1}{2}$-inch plates; this would be about 3 feet per hour with butt joints at 60 degrees and a free distance of $\frac{1}{8}$ inch.

An interesting experiment in electric welding makes use of a direct current at 200 volts and requires a metallic tank con-

taining, for example, a solution of ordinary washing soda, the solution being connected to the positive pole of the supply source. The tongs are connected to the negative pole and the piece to be heated is clamped in them and immersed in the solution. The specimen soon becomes heated to a welding heat due to the film of hydrogen which collects around the negative pole (by electrolysis, ¶ 80) and greatly increases the resistance at that point. In welding, two pairs of tongs connected to the negative pole may be used simultaneously.



Fig. 252. — Hoskins Electric Furnace.

244. Electric Cautery, Blasting, Heating and Cooking. — In *surgery* a thin platinum wire heated to a white heat by the current is used for many operations instead of a knife. Platinum is chosen because it is the most refractory metal; but even this is readily fused when the current is too strong.

In *blasting* the fuse is surrounded by some combustible material in proximity to the explosive. A current sent from a distant battery, through copper wires, melts the fuse or heats the platinum wire, as the case may be, and the combustible is ignited and the powder exploded.

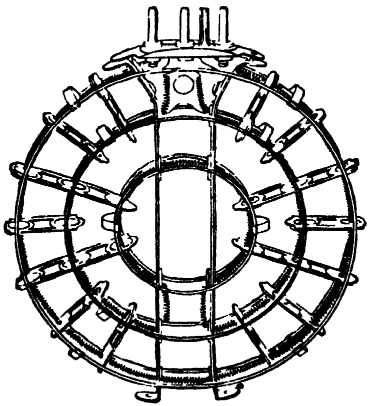


Fig. 253. — Heating Element of Electric Grill.

The heating effect of the electric current is also utilized in *electric furnaces* of various sorts for carrying on a number of industrial tests and processes. Fig. 252 shows a Hoskins electric furnace of the tube-chamber design and also a nickel-chromium resistance or heating element. The furnace is designed so that the heating elements can be replaced quickly in case

some are damaged. The crucible- and muffle-chamber designs of furnace are also much used in chemical and metallurgical work. Very large furnaces of various types are used for melting and refining steel. A 10-ton Héroult arc furnace served by a 3000-kw., 25-cycle transformer requires electrical energy to produce steel at a rate of about 600 kw.-hrs. per ton.

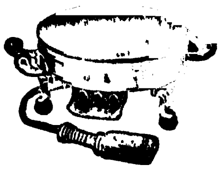


Fig. 254. — Disk Stove.

In *electric cooking* utensils, the heating element of non-oxidizing alloy may be either open or enclosed, and may be formed of a flat ribbon wound on sheet mica or of a round wire wound into a coil and supported in mica. An open-coil heating element used in a well-known electric grill is shown in Fig. 253. In the electric disk stove (Fig. 254) the heating element is enclosed. Another useful electric heating appliance, the electric iron, is shown in Fig. 255, the heating element shown in the lower part of the figure being a flat metal ribbon wound on sheet mica and enclosed within the iron shell. Fig. 256 shows the heating chamber of electric percolators, samovars, etc., in which A is the heating element mounted on and between mica, and B is a safety fuse. This fuse is a piece of lead secured to the fuse plug, and the plug is inserted in the appliance, the lead strip is in contact with the two connecting ears shown

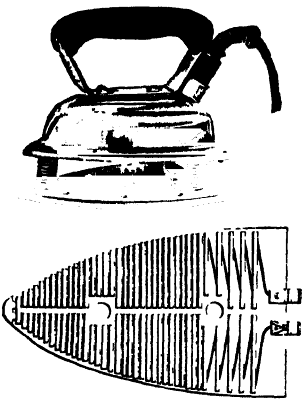


Fig 255. — Electric Iron and Its Heating Element.

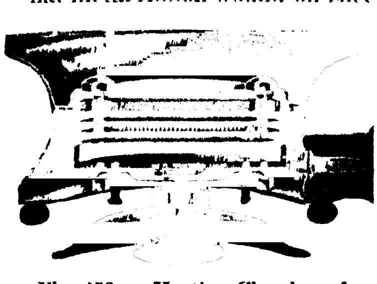


Fig. 256. — Heating Chamber of Percolators.

above B and thus closes the circuit. This safety fuse used in appliances for heating liquids is melted by the heat in the heating chamber and not by the current flowing through it as is the case with fuses used for the protection of electric circuits (¶ 212). If the liquid should boil dry while the current is on, the piece of lead will melt and automatically open the circuit, preventing the possibility of an overheated element and consequent harm to the appliance. An electric range and oven made by the Simplex Electric Heating Co. is illustrated in Fig. 257, in which the elements are of the enclosed type.

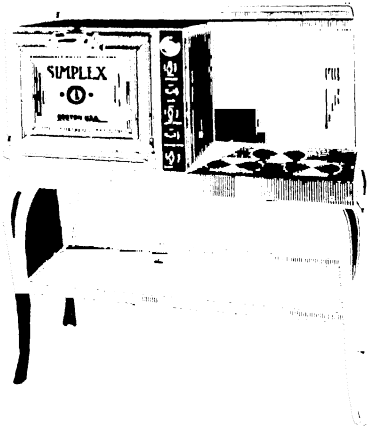


Fig. 257. — Electric Oven.

An electric heating pad, which takes the place of a hot-water bottle, is useful in many cases of illness. One type, the "Universal" heating pad, made by Landers, Frary & Clark Co., consists of a long flexible coil of high resistance wire enclosed in a pad made of asbestos, the pad being quite flexible. The heating pad has three degrees of heat, as follows: low, medium and high, these being controlled at will by the user. In series with the heating coil are four thermostats that are also enclosed inside the pad, their function being to open the heating coil circuit when the pad reaches a predetermined temperature and prevent any possibility of overheating. The thermostats, which are in series with the heating coil, are placed in circuit by the control

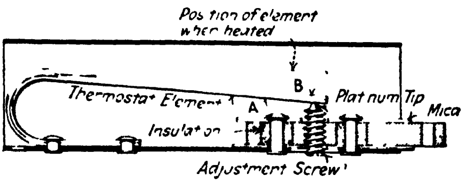


Fig. 258. — Thermostat of the "Universal" Heating Pad.

switch according to the degree of heat desired: a thermostat set for a temperature of 125° F. being in circuit on the low point of control, one set for 160° F., being in circuit on the medium point and two thermostats, each set for 195° F., being in circuit on the high temperature point. The construction of one of these thermostats is shown in Fig. 258; it consists of a metal strip bent in the shape of a hair pin and composed of two different metals, A and B, of which A will expand more rapidly than B upon an increase of temperature. One end of the strip is held securely while the other end is free to move. In Fig. 258, the free end is shown resting on a platinum-tipped adjusting screw and thereby closing the circuit, the dotted lines in the figure show the position of the free end of the thermostat element when it expands due to the temperature reaching the value for which it is set to open the circuit.

245. Measurement of Temperature by Resistance Change — Pyrometry. — It was pointed out in ¶ 241 that the resistance of a metallic conductor depended upon its temperature, increasing as the temperature increases. The manner in which the change of resistance takes place was indicated by Equation (96), viz:

$$R_1 = R\,[1 + (a \times T)],$$

where R is the resistance at the initial temperature, R_1 is the resistance at a temperature T degrees higher, and a is the temperature coefficient of resistance (or the resistance change per ohm per degree). If R and R_1 be measured for a particular metal whose coefficient a is known, it is possible to obtain the only other unknown factor in the equation, namely the temperature rise T. Thus, by transposition, Formula (96) becomes

$$T = \frac{1}{a}\left(\frac{R_1}{R} - 1\right) = \frac{R_1 - R}{a \times R}. \qquad (97).$$

Consequently, temperatures may be measured by observing the resistances of a coil of wire at those temperatures. This method of temperature measurement is sensitive and may be employed over the range from the lowest temperatures to over 1200° C. by utilizing an appropriate material (usually platinum) for the resistance coil. The measurement of high temperatures is spoken of as *pyrometry*.

In order to eliminate the resistance of the wires leading from the coil to the resistance measuring instrument, a third wire is frequently connected to the coil as shown in Fig. 259, which illustrates a Wheatstone bridge for the measurement of resistance. Herein A and B are the ratio or bridge arms, C is the rheostat arm, and the resistance coil P forms the fourth arm of the bridge. The connecting cord between the coil P and the bridge may be of any convenient length and is formed of the three numbered wires. It will be noted that wires 1-2 and 2-3 are in the C arm and wires 2-3 and 4-5 are in the P arm; consequently, by making the wires exactly of the same size, the resistance of the leads is eliminated. Then the resistance of coil P is given by the relation (see ¶ 232), P = (A × C) ÷ B.

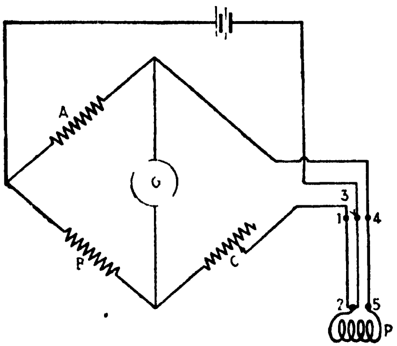


Fig. 259. — Three-lead Resistance Thermometer.

For convenience, an ohmmeter (¶ 235) or a differential galvanometer may be used as the resistance measuring device, their scales being graduated directly in degrees C. or F. The Leeds & Northrup Co. makes a resistance thermometer, utilizing a coil of nickel wire, particularly adapted for measuring the internal temperatures of electrical machinery, the indicating instrument being virtually a differential millivoltmeter.

246. Thermo-electric Pyrometers. — Another electrical method of measuring temperature is widely used; it utilizes a *thermo-couple*. If an electric circuit is formed of two dissimilar metals and one junction of those metals is subjected to a higher temperature than the other, a current is produced in that circuit due to the development of *contact electromotive forces* at the junctions. Over certain ranges of temperature, the strength of the current produced by such a thermo-couple is found to be proportional to the difference of the temperatures. Consequently, by keeping one junction at constant

temperature and subjecting the other to the temperature under measurement, the latter temperature may be determined by observing the current produced.

A variety of metals are used to form thermo-couples, and are broadly classed as rare-metal and base-metal couples. Of the former about the most satisfactory couple is that of Le Chatelier, which has one element of platinum and the other of an alloy of 90% platinum and 10% rhodium; of the latter the copper-constantan couple is frequently used for the range from 500° C. to the lowest temperatures. The following table show the electromotive forces available with these junctions at various standard temperatures, the cold junction being kept at 0° C.

Table XV. Temperature Millivolt Relations of Thermo-couples

Point	Degree Centigrade	Degrees Fahrenheit	E. M. F. in Millivolts Le Chatelier Couple	Copper-Constantan Couple
Water b.p.	100	212	0.643	4.276
Naphthalene b.p.	217.9	427.8	1.585	10.248
Tin m.p.	231.9	449.0	1 706	11.009
Benzophenone b.p	305.9	582.6	2.365	15.203
Cadmium m.p.	320.9	609.6	2.503	16.083
Zinc m.p.	419.4	786.9	3.430	
Sulphur b.p.	444.5	920.1	3.672	
Antimony m.p.	630.0	1166	5.530	
Aluminum m.p.	658.7	1217.6	5.827	
Silver m.p.	960.2	1760 3	9.111	
Gold m.p.	1062.6	1944.6	10.296	
Copper m.p.	1082.8	1981.0	10.534	
$Li_2 Si O_3$ m.p.	1201	2193.8	11.941	
Diopside m.p.	1391.5	2536.7	14.230	
Nickel m.p.	1452.6	2646.6	14.973	
Palladium m.p.	1549.5	2821.1	16.144	
Platinum m.p.	1755	3191	18.608	

The construction of two forms of base-metal thermo-couples is shown in Fig. 260. At the top are shown two dissimilar wires about one-tenth inch in diameter twisted together at one end and welded; the wires themselves are insulated from each other by porcelain beads. The lower illustration shows the inner metal rod welded to the outer tube and also the insula-

tion between them. The thermal junction may be placed in a furnace or in molten metals for ascertaining their temperatures, but they must be protected from furnace gases or from direct contact with those liquids. The external appearance of the hot junction or *fire rod* together with a thermos-bottle cold-junction device is shown in Fig. 261, which depicts a plati-

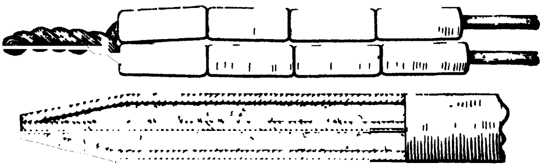


Fig. 260. Construction of Thermo-couple.

num couple for use in molten brass. This couple, made by the Pyroelectric Instrument Co., is insulated by two-hole insulators, and these in turn are enclosed in quartz; this quartz tube is enclosed with a nichrome tube and over this is a sectional graphite protection tube. The instrument for measuring the current (or E. M. F.) has its scale graduated in degrees.

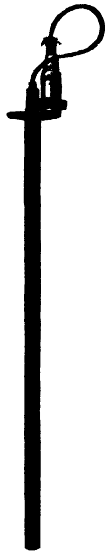


Fig. 261. — Pyrometer Thermocouple.

QUESTIONS

1. A cell is short-circuited by a thick piece of copper having a low resistance as compared with that of the cell. Where will the most heat be developed?

2 Cite an experiment to prove that heat developed in a circuit is proportional to the square of the current.

3. Equal lengths of No. 10 and No 20 B. & S gage copper wire are connected in series and to a generator. Is there any difference in the strength of current through, or heat evolved from, the two wires?

4. A thermometer is immersed in a vessel containing dilute sulphuric acid and a plate of zinc and of copper When the extremities of the plates are connected by a wire the temperature rises. Explain this.

5. The size of wire for carrying 62 amperes is calculated by voltage drop to be, in a certain instance, No. 6 B. & S. Would you use a rubber insulated wire of this size? Why?

6 Explain the method of temperature measurement by means of resistance change.

PROBLEMS

1. How many heat units are evolved in 10 hours from an arc lamp requiring 10 amperes and 45 volts? *Ans.* 15,352 B. T. U.

2. How many pounds of water can be raised from 80° F. to the boiling point by the heat evolved in Problem 1, neglecting all losses? *Ans.* 116.3 lbs.

3. With an E. M. F. of 110 volts what current must be passed through a coil of iron wire, immersed in 2 pounds of water so that it will boil in 45 minutes? The temperature of the water at the start is 60° F. *Ans.* 1.08 amperes.

4. The hot resistance of an electrical laundry iron is 22 ohms and it is connected across 110-volt mains. Suppose the iron to be placed into a vessel containing 8 pounds of water, the temperature of which is 60° F., and the current turned on for 15 minutes. What will be the temperature of the water at the end of that time, not deducting losses for radiation, etc.? *Ans.* 118.6° F.

5. Give the equivalent amount of energy in joules and foot-pounds expended in the arc lamp in Question 1. *Ans* 16,200,000 joules; 11,950,000 ft.-lbs.

6. The length of a power cable is 600 feet, and the size of the conductor is No. 4 B. & S. gage. Suppose that the temperature of the cable on a summer day is 104° F., and on a winter day is 10° F. (a) What will be the resistance of the cable in each case? (b) If the cable is delivering 30 kw. at 1100 volts, what will be the lost power on the line at the summer temperature as above? (c) What will be the cost of this loss when operating 5 hours a day for 6 months (180 days) with energy costing $7\frac{1}{2}$ cents per horse-power-hour? *Ans.* (a) 0.165 ohm at 104° F., 0.130 ohm at 10° F.; (b) 123.3 watts; (c) $11.17.

7. A nickel coil of a resistance thermometer has 5 ohms resistance at 0° C. At some other temperature its resistance is 7.48 ohms. What is that temperature if nickel has an average temperature coefficient of 0.0062 per Centigrade degree? *Ans.* 80° C.

LESSON XXI

ELECTRIC LIGHTING

Arc Lamps — Flaming and Magnetite Arc Lamps — Mercury Vapor Lamps — Incandescent Lamps — Rating and Efficiency of Incandescent Lamps — Table XVI — Light Distribution Curves — Calculation of Lighting Installations — Tables XVII and XVIII — Incandescent Lamp Circuits — Wiring Calculations — The Three-Wire System — Questions and Problems.

247. Arc Lamps. When an electric current under a pressure of about 45 volts, is passed through two carbon rods, with their ends first in contact and afterward gradually separated a short distance, as one-eighth inch, a brilliant arc of flame called the *electric arc,* is established between them. The high temperature caused by the passage of the current through the resistance of the contact surfaces causes the carbon to vaporize and the vapor thus arising, being a much better conductor than the air, conducts the current across the gap from one carbon tip to the other. As the arc is maintained across the gap, disintegration of the carbon takes place, the carbons waste away, and a cup-shaped depression, termed the *crater,* is formed in the *positive carbon,* while the tip of the negative carbon assumes a conical form, Fig. 262. The consumption of the positive carbon is about twice as rapid as that of the negative.

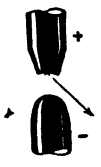


Fig. 262. — Arc-lamp Electrodes.

Most of the light comes from the crater formed in the upper or positive carbon, and but little from the incandescent carbon vapor. The light is largely thrown downward and has the greatest intensity at an angle of about 45° below the horizontal. In an alternating arc lamp, the crater alternates from one carbon to the other with each reversal of current, so that both carbons are consumed about equally, the light being emitted from both carbon tips with equal intensity. Automatic devices feed the carbons as they are consumed, and thereby maintain the proper length of arc. This is accomplished by a suitable arrangement of mechanical movements actuated with series and shunt solenoids.

Arc lamps for street lighting are usually operated in series on *constant-current circuits* because the lamps are distributed over a large area and the energy can be more economically supplied with a small current at a high pressure. Arc lamps for interior lighting are operated in multiple on *constant-potential* circuits. At present relatively few arc lamps are in use owing to the development of large size gas-filled incandescent lamps, ¶ 250.

The arc lamps now used for spot lights and for stereopticon and motion-picture projection do not have their carbons placed in a common vertical line as have the lamps described above,

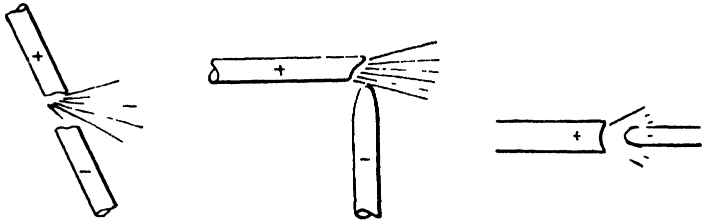


Fig. 263. Fig. 264. Fig. 265.
Arrangement of Carbons in Focusing Lamps.

but employ arrangements such as shown in Figs. 263 to 265 in order to throw as much light as possible toward the condensing lenses of the projector. The carbon placement shown in the latter figure is often used in motion-picture projection, the light from the positive carbon being directed upon a concave reflector, which redirects the light in a converging pencil upon the film without the use of condensing lenses.

In arc lamps designed for search-light projectors the carbons may be either inclined or horizontal; the arc, however, is always directed towards the reflector and away from the object to be illuminated. The carbons may be fed by hand, or automatically by means of a solenoid, the positive carbon being moved faster than the negative in order to keep the crater at a given point.

248. Flaming and Magnetite Arc Lamps. — For lighting large areas outdoors, flaming arc and magnetite arc lamps are used; they are rarely employed for indoor illumination because of the obnoxious fumes given off. In the *flaming arc* lamp,

Fig. 266, carbon electrodes are used having a core made up of a mixture of powdered carbon, mineral salts and a suitable binder. The presence of mineral salts in the carbon produces between the arc terminals a vapor path conveying the particles of light-producing substances. Owing to the presence of these substances in the arc, the temperature of the carbon is reduced, so that they produce very little light, and nearly all of the illumination comes from the arc flame. The arc is enclosed in a glass globe to which the supply of air is limited by an air-circulation chamber, and the fumes are deposited in a condensing chamber.



Fig. 266. Enclosed Flame Arc Lamp.

In most open flaming arc lamps, both carbons are fed point downward at an angle to each other, thus obtaining maximum illumination without interference and shadows. Some flaming arcs, however, particularly of the enclosed type, have the carbons arranged in a vertical line, as in the ordinary arc. The lamp requires about 45 to 70 volts at the arc and from 8 to 10 amperes. Flaming arc lamps, because of their very high candle-power, are suited for display and advertising purposes.

The *magnetite arc* is so called because it uses magnetite, one of the oxides of iron, as the negative electrode, the magnetite being in the form of powder and tightly packed in a steel tube. The positive electrode is copper. In one type of this lamp the negative electrode is placed at the top and in another at the bottom. The magnetite lamp (Fig. 267) has a white dazzling flame arc of great intensity but small volume. The lamp is particularly adapted for street lighting, since, owing to the slow consumption of metal in the arc, frequent trimming is not required. A standard type of lamp for street lighting requires a direct current of 4 amperes and 78 volts at the arc; its mean spherical candle-power is 250.

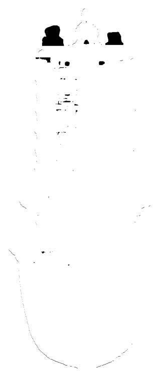


Fig. 267. — Magnetite Arc Lamp.

249. Mercury Vapor Lamps. — The mercury vapor lamp, Fig. 268, derives its light from the vapor of mercury in which the passage of an electric current causes incandescence. The lamp consists essentially of a glass tube over four feet in length



Fig. 268 — Cooper Hewitt Mercury Vapor Lamp.
Produces 875 mean hemispherical c. p. with 3.8 amperes at 115 volts

containing mercury vapor at low pressure, and having at the positive terminal a piece of iron and at the negative terminal a pool of mercury. Inductance (¶ 268) and resistance are placed in series with the lamp to counteract any effect caused by a variation in voltage, thus permitting the lamp to operate steadily.

When the lamp is not illuminated, the resistance between the negative electrode and the vapor is very high; this must be overcome before the lamp can be put in operation. A simple method of starting the lamp is merely to tilt the tube until the two electrodes are brought in contact by a thin stream of mercury along the length of the tube, and then allow the lamp to return to its normal position; an arc is started by breaking the mercury stream, causing the volatilization of the mercury, the vapor filling the tube and becoming incandescent. Modern lamps, however, are started automatically.

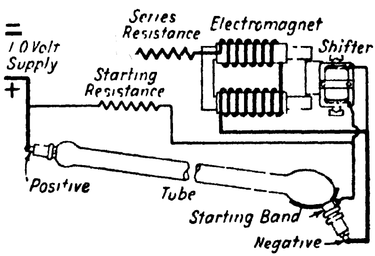


Fig. 269. — Connections of a Direct-current Mercury Vapor Lamp.

The connections of a Cooper Hewitt direct-current lamp are given in Fig. 269. The automatic starting device is known as a *shifter*, and consists of a glass bulb containing mercury and mounted in a frame which

is actuated by an electromagnet. This shifter has a resistance in series with it, and this starting circuit is connected in parallel with the lamp tube. When voltage is applied to the lamp, current of about 1 ampere flows from the positive terminal through the starting resistance, shifter, electromagnet and series resistance back to the negative terminal of the supply. The electromagnet becomes energized and causes the shifter to rotate; this action separates the mercury in the shifter and interrupts the current through it. As a result a momentary high voltage is developed due to the inductance of the electromagnet, which voltage is impressed upon the tube between the negative electrode and starting band. By the aid of the condenser action of this band a hot spot of electric discharge is formed on the mercury pool and current flows through the lamp tube, the shifter being held in its open-circuit position. If the shifter current interruption does not at first start the lamp, the above operations are repeated until the lamp is lighted.

The mercury vapor lamp with its usual reflector is in effect a light source 9 inches wide by $1\frac{1}{2}$ feet long; therefore it gives a diffused light without much glare. The light is of a bluish-green color, and is relatively richer in actinic light than any other common artificial light source, consequently it is very successfully used in all kinds of photographic processes. This high actinic efficiency results not, however, from the total amount of actinic light present but from the fact that what is there has the same wave length range as that over which the photographic plate is most sensitive.

Lamps designed for operation on alternating-current circuits are provided with two positive electrodes and an auto-transformer, ¶ 357, the principle of operation being that of the mercury rectifier, ¶ 367.

250. Incandescent Lamps. In an incandescent electric lamp the light is produced by heating to a state of incandescence, a high resistance solid conductor which is not readily fused by the passage of a current through it. The light-giving element, termed the *filament*, is hermetically sealed in a vacuum or in an inert gas within a glass bulb, to prevent it from burning. The material of which the filament is composed should have a high melting point and should not be liable to a rapid rate of evapo-

ration at temperatures below the melting point. Increasing the temperature of a lamp filament increases the light given out much more rapidly than the energy needed to produce that temperature, but the rate of filament evaporation is also increased, therefore, the most efficient transformation of electrical energy into light is realized when the filament is operated at the highest temperature it can stand without causing excessive filament evaporation. Evaporation causes blackening of the glass bulb and results in a decrease in light from the lamp; it also naturally causes a gradual disintegration of the filament until it breaks.

A small glass tube containing the lead-in wires and supporting the filament is sealed into the blown-glass bulb of the ordinary shape. The bulb is connected by means of a glass stem to an air-pump and the air is exhausted; the stem is then heated and sealed, forming a pointed tip on the end of the finished lamp or concealed within the base. The lamp base consists of two pieces of brass insulated from each other, secured to the lamp bulb by cement, and arranged to screw into a *lamp socket*.

The *carbon filament* is made in the following manner: absorbent cotton is dissolved in zinc chloride and hydrochloric acid, forming a gelatinous mass a trifle thicker than molasses. This material is forced under pressure through a die, into a vessel containing alcohol which causes it to set and harden sufficiently for handling, thus forming a long thread-like filament. After washing, the material is wound upon a drum and dried, after which it possesses considerable strength. It is then gaged for size and cut into suitable lengths and wound upon forms to produce the required shape; thereafter the filaments are *carbonized*, by heating them in a furnace at a high temperature. The filament is next subjected to the "treating" process, whereby a coating of graphitic carbon is deposited thereon by flashing in an atmosphere of hydrocarbon vapor; the object of which is to insure uniformity in resistance. The filament is then ready for mounting upon the leading-in wires and is secured to them by a carbon paste.

The so-called *metallized carbon filament* is produced by heating the ordinary carbon thread in an electric furnace before and after the "treating" process, giving it the appearance and

electrical characteristics of a metal. The lamp containing this filament was placed on the market under the trade-name of "Gem" lamp, which, in appearance, is similar to the carbon lamp, Fig. 270. The metallized filament has a *positive temperature coefficient*, that is, its resistance increases with an increase in temperature, just like metals, ¶ 241. Lamps having *positive* temperature coefficients have their lowest resistance when cold, the ordinary carbon filament has a *negative* tem-

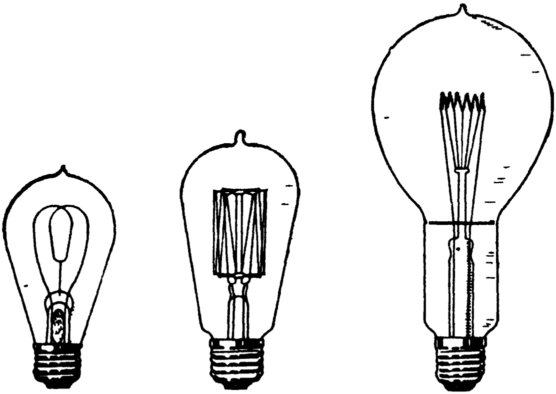


Fig. 270. — Carbon Filament Lamp.   Fig. 271. — Vacuum Type Tungsten Lamp.   Fig. 272. — Gas-filled Tungsten Lamp.

perature coefficient, since its resistance is lowest when *hot*. At present only a few per cent of the total domestic lamp sales are for carbon lamps.

The incandescent lamps now universally used contain *tungsten filaments* within evacuated or gas-filled bulbs. Tungsten (or wolfram) is a metallic element named from the Swedish "tung" (heavy) and "sten" (stone). It is not found native, but occurs as the tungstate of iron and manganese in the mineral "wolframite," and as calcium tungstate. The pure tungsten metal comes in the form of a powder, is a bright steel gray, and is hard and very heavy.

The first tungsten filaments manufactured in this country were made similar to the carbon filaments, that is, the finely

divided metallic tungsten was mixed with a binder, squirted through dies into threads, and subsequently given suitable electric and heat treatment. Methods were soon discovered for manufacturing tungsten in the form of drawn wire. The tungsten powder is pressed into ingots without a binder, and these are heated to a white heat in an electric furnace in an atmosphere of hydrogen, thus making them good electrical conductors. These ingots are then swaged and heated a number of times until reduced to a round rod sufficiently small to be drawn. This process takes place through diamond dies while the tungsten is very hot, the drawing being continued until the wire is of proper size. The filament is now wound upon spiders in long loops and fastened to the leading-in wires, as shown in Fig. 271; thereafter the bulb is exhausted of air to a very good vacuum. Such lamps, known to the electrical trade as Mazda B lamps, have a high efficiency, ¶ 251, and produce a whiter light than the Gem lamp.

The *gas-filled* tungsten lamp has its bulb filled with an inert gas, such as nitrogen, so that the tungsten wire filament can be operated at higher temperatures, and at higher efficiencies than the vacuum-type lamps. These lamps are known as Mazda C lamps, Fig. 272. The filament in the gas-filled lamps is wound in a coil of very small diameter and mounted in a compact manner upon small radial supporting arms projecting from the end of a long glass stem extending from the base. This construction concentrates the filament in a small space in the center of a pear-shaped glass bulb. While the presence of the inert gas in the bulb tends to cool the filament by the passage of the rising gas, this effect is counteracted by using the compact form of filament. The presence of the gas also reduces the rate of evaporation of the filament. Thus the lamp may be operated at even higher temperatures than is possible in the vacuum lamps. The hot gas currents also tend to carry any evaporated particles to the upper portion of the bulb (base end of the lamp) where they can be deposited without interfering with the emission of light.

Platinum was formerly universally used for lead-in wires because it has the same coefficient of expansion as glass and therefore makes a tight joint under varying temperature conditions.

Since 1914 copper-coated nickel-iron wire, called Dumet wire, has been used extensively for lead-in wires.

In lighting installations where the tungsten filaments come within the field of vision it is desirable to use lamps with a part or the entire bulb frosted or sprayed on the outside for the reduction of glare. Recently lamps of small size frosted on the inner side of the glass have been introduced; this type diffuses the light well and leaves the outside surface smooth to facilitate cleaning.

Gas-filled clear lamps with coiled tungsten filaments are very satisfactory when used with reflectors for street-car head-lights, for outdoor flood lighting, for stereopticons, spot lights and motion-picture machines.

251. Rating and Efficiency of Incandescent Lamps. — All incandescent lamps are rated by the power input in watts at the designated voltage. At a given voltage, the higher the wattage of the lamp the larger is the cross-sectional area of its filament, the lower its resistance, and consequently the greater the current taken. A 75-watt, 120-volt lamp takes a current of $75 \div 120 = 0.625$ ampere and has a resistance of $120 \div 0.625 = 192$ ohms.

The brightness of a lamp is expressed in *candle-power*, the candle being the unit of luminous intensity maintained by several national laboratories. If the candle-power of a lamp is averaged over all directions from its center, it is called the *mean spherical candle-power*. The average candle-power in a horizontal plane through the luminous center of a lamp (its axis being vertical) is termed the *mean horizontal candle-power*.

Watts per candle is a term used commercially to denote the specific consumption of a lamp in watts per mean horizontal candle-power produced. If a 100-watt Mazda C lamp yields an average intensity of illumination of 125 candle-power in a horizontal direction, its specific consumption is $100 \div 125 = 0.80$ watts per candle, abbreviated 0.80 w. p. c. Carbon lamps have specific consumptions of 2.5 to 3.5 w. p. c. in sizes up to 100 watts. The lower the numerical value of this ratio the more efficient is the lamp. The average life of incandescent lamps is figured at 1000 hours.

Incandescent lamps of all kinds give their proper candle-power

and consume their rated watts only when they are operated at the voltage indicated on the label; lamps, however, may be operated at widely different voltages, with a corresponding sacrifice of either life or light. If the voltage on a lamp is decreased, the watts and candle-power consequently decrease, while the watts per candle and the life are thereby increased, and vice versa. In any installation the rated lamp voltage should be the average operating voltage of the circuit measured at the lamps. Owing to the positive temperature coefficient of the Gem and tungsten lamps, they are not as sensitive to changes in line voltage as was the carbon lamp, this is a decided advantage on circuits where the voltage fluctuates.

The output of a lamp is the luminous flux which it produces expressed in terms of the unit called the *lumen*. For an illuminant which yields a luminous intensity of 1 candle-power in all directions the output is 4π lumens, that is $4 \times 3.142 = 12.57$ lumens. Therefore:

1 spherical candle-power emits 4π or 12.57 lumens,
1 lumen is emitted by 0.0796 spherical candle-power.

Lamp efficiency is the ratio of the light output in lumens to the electrical input in watts, and is accordingly expressed as so many lumens per watt.

TO DETERMINE THE EFFICIENCY OF A LAMP:

Multiply the spherical candle-power by 12.57 and divide by the power consumption in watts.

Or

$$\text{efficiency} = \frac{\text{lumens}}{\text{watts}} = \frac{12.57 \times \text{c.p.}}{P} \quad \ldots\ldots\ldots \quad \textbf{(98)}.$$

Problem 116. — What is the efficiency of a 200-watt lamp which produces a mean spherical candle-power of 258?

By Formula (98)

$$\text{efficiency} = \frac{12.57 \times 258}{200} = 16.2 \text{ lumens per watt.}$$

The following table gives the sizes and efficiencies of vacuum and gas-filled 115-volt tungsten lamps now in general lighting service:

Table XVI. Tungsten Lamp Efficiencies

Mazda B		Mazda C	
Watts	Initial Lumens per Watt	Watts	Initial Lumens per Watt
10	6 6	50	10 4
15	8 9	75	12 2
25	9 5	100	13 4
40	10 2	150	15 0
50	10 3	200	16 2
60	10 5	300	17 0
		500	18 8
		750	19 2
		1000	20 0

The output of a lamp is generally measured by placing it within a sphere having a diffusing inner surface and comparing the brightness of a translucent window located on the surface with the illumination produced by a traveling calibrated lamp. Fig. 273 shows a 40-inch sphere photometer made by Foote, Pierson and Company for the measurement of lamps up to 1000 candle-power and 1000-watt sizes. The revolvable double door supporting the two lamp sockets enables the measurement of one lamp while another is being changed in the socket then on the exterior of the sphere.

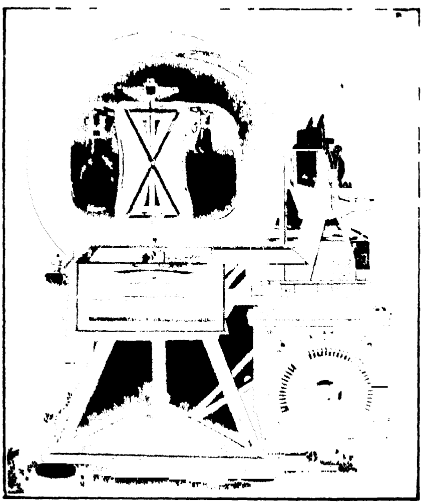


Fig. 273 — Integrating Sphere Photometer. Complete with voltmeter, rheostats and Lummer-Brodhun photometer

252. Light Distribution Curves. - The brightness of a lamp is not the same in all directions. For example, a carbon-filament lamp may show 16 candle-power in a horizontal direction, but only 8 candle-power in a direction through the tip of the lamp. In order to show the intensity of light available in any direction it is customary to plot a *polar distribution curve*, Fig. 274, in which the radial lines represent by their lengths the candle-powers available in the direction in which they are drawn. The illustration shows the light distribution in a vertical plane for a clear-glass, 50-watt carbon-filament lamp.

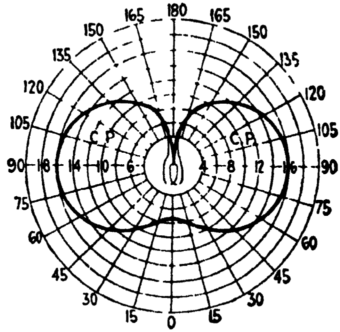


Fig. 274. - Vertical Light Distribution of a Carbon-filament Lamp.

In lighting installations, the lamps are mounted in fixtures with shades or reflectors, in order to yield the proper intensity and uniformity of light where it is desired. Reflectors serve primarily to redirect a portion of the light, by means of mirrors or by polished aluminum, enamel or mat glass surfaces. Shades serve chiefly to conceal the light source so as to avoid glare, although they may serve in part as reflectors; they are made of translucent glass and many are designed primarily for decorative purposes. A number of reflectors and shades are outlined in Fig. 275 together with their light distribution curves; the numbers in the columns headed "Light Output" show the percentages of light above and below the horizontal plane through the lamp.

253. Calculation of Lighting Installations. The illumination produced upon a surface is the quantity of light flux which is intercepted by unit area of that surface. For example, if 30 lumens of light flux fall upon a surface of 15 square feet, the illumination is 30 ÷ 15 = 2 lumens per square foot; this intensity is more commonly called 2 *foot-candles*. Intensities of illumination recommended for various classes of lighting service are given in the following table:

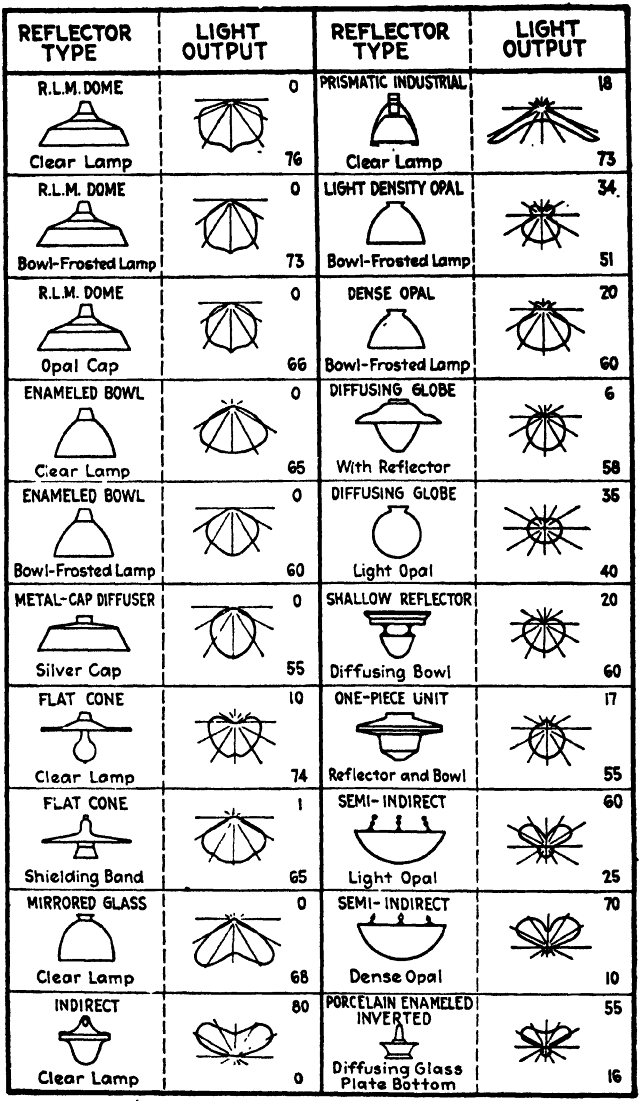


Fig. 275. — Reflectors and Shades with their Light Distribution Curves.

Table XVII. Intensities of Illumination

	Foot-candles
Auditoriums, churches	2–4
Armories, exhibition halls	3–6
Corridors, stairways	1–2
Drafting rooms	10–15
Foundries, forge shops, boiler rooms	3–6
Industrial yards	0.2–0.5
Instrument shops	6–15
Laundries, machine shops	5–10
Offices	6–10
Schools, libraries	4–8
Show windows	10–70
Stores	4–10
Tool rooms, press rooms, textile mills	8–16

Light produced by a source or several sources of illumination within a room or other enclosure is entirely absorbed by the surfaces in the enclosure. If the light which reaches an arbitrary working plane say 30 inches above the floor be considered the useful light, then the useful light is less than the total light flux produced in the enclosure by the amount of flux absorbed by walls and ceiling. The percentage of light flux which reaches the working plane is termed the *utilization factor*, and it naturally depends upon the darkness or lightness of walls and ceilings and upon the type of lighting fixture used. Values of this utilization factor for a few types of reflectors, Fig. 275, with clear lamps are given below, allowance being made for normal dust collection:

Table XVIII. Utilization Factors

	Light walls and ceiling	Dark walls and ceiling
RLM Dome	0.49	0.44
Enameled bowl	0.41	0.37
Metal-cap diffuser	0.35	0.31
Diffusing globe	0.37	0.30
Semi-indirect (light opal)	0.34	0.19
Semi-indirect (dense opal)	0.29	0.14
Indirect	0.27	0.10

To illustrate the calculation of a lighting installation assume a machine shop 60 feet × 24 feet × 14 feet having light walls and ceiling. From Table XVII it is seen that 7 foot-candles

will provide suitable illumination; this means that each square foot should receive 7 lumens; consequently the entire working plane requires 7 × 60 × 24 = 10,080 lumens. For RLM Domes the utilization factor is 0.49 as given by Table XVIII, and therefore the light flux which must be emitted by the lamps is 10,080 ÷ 0.49 = 20,600 lumens. For a ceiling height of 14 feet this type of lighting unit will provide uniform illumination with a spacing of 12 feet between units. Placing a lamp at the center of each 12 foot square requires 10 units, each providing 2,060 lumens. Table XVI shows that the 150 watt Mazda C lamp produces 150 × 15.0 = 2,250 lumens; consequently the installation will require ten such lamps.

254. Incandescent Lamp Circuits. Incandescent lamps are usually operated from 110- to 125-volt constant-potential (*i.e.* multiple) circuits and supplied by direct or alternating current. With a potential of 600 volts, as in street car service, the lamps are grouped in multiple-series; for example, five 120-volt lamps in series being placed across the mains. For street lighting, a constant-current series incandescent lamp system is sometimes employed, in which each lamp socket is provided with an automatic cut-out which short-circuits the filament of the lamp in case of failure or burn-out. In the series system the same current flows through all the lamps and is maintained constant, consequently all lamps for such a system should have the same current rating. Low-voltage lamps for series burning are constructed with filaments of large area to carry the large currents. Such lamps with tungsten filaments are made to carry currents from 4 to 20 amperes.

In multiple circuits, the voltage drop in the mains is an important factor, ¶ 132, and requires that the lamps be so distributed, and the size of the wire so proportioned, that each lamp will receive approximately, the same voltage. To do this, *centers of distribution* are planned in wiring construction, and the lamps are grouped so as to be supplied from these centers. Feed wires are run from the generator to the points of distribution and a constant potential is maintained at these points by regulation at the generator. No lamps are connected to the feeders. Several sets of mains are run from these centers and supply sub-centers of distribution, to which the lead wires

to the lamps are connected. The total drop or fall in voltage from the generator to the lamps in such a feeder-and-main system, radiating from a central supply station, may be 5 to 10 per cent of the generator voltage, so that the generator should be operated at a correspondingly higher voltage than that required by the lamps. In the wiring of a house for about 50 110-volt lamps of average size, the drop in voltage, at full load, should be about 2 per cent of the pressure supplied at the service mains. With an isolated plant in a large office building the drop may be 5 per cent of the generator voltage.

255. Wiring Calculations. The size of wires required to conduct current from the service mains to the lamps can be calculated when the total current required by the lamps and the permissible voltage drop in the line wires are known. A formula for the wire size in circular mils is derived by combining Formulæ (10) and (29), which are respectively:

$$R = \frac{K \times L}{C.M.} \quad \text{and} \quad R = \frac{e}{I},$$

where C. M. = cross-sectional area in circular mils,
K = resistance of 1 mil-foot of wire,
L = length of circuit in feet,
I = current in amperes,
e = volts drop on the line.

Equating these formulas, there results,

$$C.M. = \frac{K \times L \times I}{e}.$$

Copper being generally used as the conductor, K = 10.79, and this formula becomes

$$C.M. = \frac{10.79 \times L \times I}{e} \quad \ldots\ldots\ldots\ldots\ldots \quad \textbf{(99)}.$$

To find the size of copper wire in circular mils to conduct any given direct current a certain distance with a given drop on the line:

Multiply the total length of the line, in feet, by the resistance of a mil-foot of copper wire, namely 10.79, *and this product by the current, in amperes, to be conducted; divide this product by the volts drop on the line.*

The circular mil area so found must be compared with the table of current-carrying capacities, page 306. By using a very excessive drop on the line the circular mil area calculated by Formula (99) in some cases would be much too small for the current to be conducted, hence the necessity of using the table of carrying capacities as a check upon the calculations. *Usually the distance from the generator to the center of distribution is given and consequently this distance must be multiplied by 2 for the two-wire multiple system, to obtain the total length of the circuit, L in Formula (99).*

Problem 117. One hundred and ten 50-watt 110-volt lamps are connected in parallel and to a center of distribution located 125 feet from the generator which develops a P. D. of 113 volts, the potential at the distributing center is to be 111 volts. What size wire is required for the feeder?

By Formula (55) the total current is $I = \frac{P}{E} = \frac{50 \times 110}{110} = 50$ amperes

The drop on the line is $e = 113 - 111 = 2$ volts.

By Formula (99) $C.M. = \frac{10.79 \times 125 \times 2 \times 50}{2} = 67{,}437$ C. M.

Consulting the table, page 67, the size of wire nearest to 67,437 C. M. is No. 2 B. & S. with a circular mil area of 66,370, which is smaller than that required. It is better to use the next larger size of wire, or a No. 1 B. & S., which will give a little less drop than 2 volts. Consult the table of safe current-carrying capacity, page 306, and it will be found that No. 1 can carry 100 amperes. A much smaller wire could have been used in this problem, as a No. 5, which carries 55 amperes, but the line drop and loss would then have been correspondingly larger, since the resistance of the circuit is increased.

256. The Three-Wire System. Most central stations distribute electrical energy for lighting and power with the *three-wire system*. In this system two generators (see ¶ 305) may be joined in series, and the lamps connected between a center or neutral wire which is connected to the junction of the machines, and the positive and negative wires of the system, as shown in Fig. 276. When all the ten lamps illustrated are in circuit, no current will flow through the middle wire, and it can be disconnected at the generators without affecting the system. If

only three lamps are connected on the No. 1 side of the system, then current for the two extra lamps not paired flows through the middle wire from the + brush of No. 2 generator. The middle wire is now positive. If three lamps are out on the No. 2

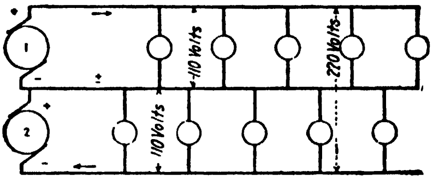


Fig. 276—Incandescent Lamps Operated in Parallel from the Three-wire System.

side of the system, then current for the three lamps on the No. 1 side flows from the + terminal of generator No. 1 and returns to it by the middle wire, which is now negative. The middle wire, therefore, may have no current flowing through it, or current flowing in either one direction or the other, depending upon how closely the lamps on both sides of the system are balanced; for this reason it is called the neutral wire. Motors wound for 220 volts are connected to the two outside wires and do not interfere with the load balance.

The chief advantage of using the 3-wire system is the saving effected in copper, only $\frac{3}{8}$ as much copper being required as in the 2-wire system. The E. M. F. across the outer wires is double that of the 2-wire system, so that the current required for any given load is reduced to half. With the same percentage voltage drop, the drop in volts is twice as great. Consequently, to transmit half the current at twice the voltage drop, means that the wires may have 4 times the resistance. Each wire of the 3-wire system will then be one-quarter as heavy as in the 2-wire system; since an extra wire is required in the former, this system needs $\frac{3}{8}$ of the copper used in the 2-wire system.

QUESTIONS

1. What is the distinction between an arc and an incandescent lamp?
2. From what part of the arc is the most light emitted and what is the general direction of maximum intensity?
3. Why are lamps used for street lighting generally operated in series?

4. Describe the mercury-vapor lamp.

5. What are the advantages of the tungsten filament lamp over the carbon lamp?

6. What is the advantage of the three-wire distribution system over the two-wire system?

7. How are incandescent lamps rated as to size and efficiency?

8. What is a lumen and how is it related to a candle-power?

9. Sketch the light distribution curve of a semi-indirect lighting fixture.

10. In what units is the intensity of illumination reckoned?

11. Design a lighting installation for a class room or school auditorium.

PROBLEMS

1. A 110-volt, 20-c. p. carbon lamp requires 50 watts. Give the following: (*a*) specific consumption of energy; (*b*) lamps per H. P.; (*c*) cost of operating the lamp for 100 hours if the energy costs 10 cents per kw.-hour; (*d*) efficiency. *Ans.* (*a*) 2.5 w. p. c.; (*b*) 15 lamps; (*c*) \$0.50; (*d*) 5.03 lumens per watt.

2. A 25-watt Mazda lamp has a specific consumption of 1.25 watts per candle. Give the following: (*a*) candle-power produced; (*b*) lamps per H.P.; (*c*) cost of operating this lamp for 100 hours, if the energy costs 10 cents per kw. hour? *Ans.* (*a*) 20 c. p.; (*b*) 29 lamps; (*c*) \$0.25.

3. Two hundred 50-watt 110-volt lamps are connected in parallel and are fed from a center of distribution located 100 feet from the generator. What size of wire will be required, if $2\frac{1}{2}$ volts are to be lost on the main feeders? *Ans.* No. 1 B. & S.

4. If 25-watt Mazda lamps were used in Problem 3, what size wire would be required, allowing 2 volts loss on the line? *Ans.* No. 3 B. & S.

5. A series arc circuit, 5 miles in length, is constructed of No. 6 B. & S. wire and carries 10 amperes. (*a*) What is the voltage drop on the line? (*b*) What power is lost on the line? (*c*) What is the yearly cost of the power lost on the line, operating 10 hours a day for 365 days at 5 cents per kw.-hour? *Ans.* (*a*) 108.5 volts; (*b*) 1085 watts; (*c*) \$198.

6. The lamps in Problem 3 are to be supplied from a three-wire multiple system. What size wire will be required? *Ans.* No. 5 B. & S. (when checked by Table XIII).

7. A 30-ampere 30-volt motion-picture Mazda C lamp has an efficiency of 27.4 lumens per watt. (*a*) Determine its spherical candle-power. (*b*) Calculate the watts per spherical candle-power. *Ans.* (*a*) 1962 c. p.; (*b*) 0.46.

8. A Mazda C series street lighting lamp takes 6.6 amperes, consumes 153 watts and produces 2500 lumens. Determine (*a*) the voltage across the lamp, and (*b*) its efficiency. *Ans.* (*a*) 23.2 volts; (*b*) 16.3 lumens per watt.

LESSON XXII

ELECTROMAGNETIC INDUCTION

Electromagnetic Induction — E. M. F. Induced in a Wire by a Magnet — To Find the Direction of the Induced E. M. F. — Value of the Induced E. M. F. — Lenz's Law of Induced Currents — Variation of Induced E. M. F. with the Rate of Change of Magnetic Lines of Force — Eddy Currents — Magnetic Hysteresis — Mutual Induction — Self-Induction — The Spark Coil — Inductance — Neutralizing the Effects of Self-Induction — Principle of the Induction Coil — Action of the Condenser — Construction of Induction Coils — Table XIX — Induction Coils for Automobile Ignition Systems — Questions.

257. Electromagnetic Induction. — In Lesson XIII, a current of electricity flowing through a wire was found to set up around the wire a magnetic field (Fig. 125). If a wire is arranged so as to form a closed circuit and is then moved across a magnetic field so that it will cut the magnetic flux, a current of electricity is produced in the wire; in other words, if a magnetic flux is artificially produced around the wire, a current of electricity will flow through it when the circuit is complete. The English physicist, Michael Faraday, discovered (in 1831) that electric currents could be produced in a closed circuit by moving magnets near it, or by moving the circuit across a magnetic field. In order to have an electric current flow through a circuit there must be an E. M. F., therefore, when a wire is made to cut magnetic flux, there is first set up at the terminals of that wire an *induced E. M. F.*, and when the circuit is completed, a current will flow in consequence of this induced E. M. F. Currents that are so generated are known as *induction currents* and the phenomenon termed *electromagnetic induction*. This is a most interesting and valuable branch of the study of electricity, as upon its principles is based the operation of many forms of commercial electrical apparatus, such as dynamos, transformers and induction coils.

258. E. M. F. Induced in a Wire by a Magnet. — Consider a copper wire connected to a sensitive galvanometer, G (Fig. 277), and so located that a portion AB is within the influence of the bar magnet NS. If the wire AB is *quickly moved down* past the pole of the magnet a *momentary current* will flow in the wire due to the induced E. M. F., causing the galvanometer needle to be deflected, say to the right of zero, after which it will again return to the zero position. If the wire is again *moved up* past the same pole another *momentary current* will flow in the wire in the *opposite direction* to the former current, as indicated by the *momentary deflection* of the galvanometer needle which now swings to the left of zero. If the induced current, then, flows from B to A on the downward motion it will flow from A and B on the upward motion. If the wire be moved rapidly up and down past the magnet, the current will alternate in direction with each direction of motion, or an *alternating current* (¶ 325) will flow in the wire. When this motion is rapid, and consequently the alternations rapid, the needle does not have sufficient time to take up the respective positions due to the opposite currents traversing the instrument and will remain at zero, appreciably vibrating, however.

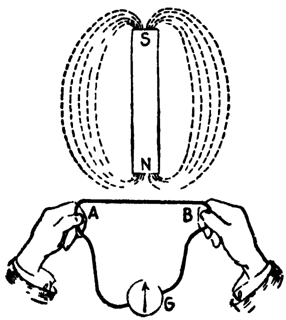


Fig. 277. – Current Established in a Wire by Moving It near a Magnet

(1) *If the wire is held stationary and the magnet moved, the same results are noted.*

(2) *If the opposite pole of the magnet is used, the direction of the induced E. M. F. and of the current in each instance is opposite to what it was before.*

(3) *An electromagnet used instead of the permanent bar magnet will produce the same results.*

(4) *The current in the circuit does not weaken the magnet, but is produced by the expenditure of muscular energy, just as in a cell the current is produced by the expenditure of chemical energy.*

(5) *The momentary induced E. M. F. is greatest when the*

wire is moved so as to cut the magnet lines of force, at right angles.

(6) *If the wire in Fig. 277 does not form a closed circuit, an E. M. F. will still be induced in the wire when motion occurs and be available at its terminals, just as an E. M. F. exists at the terminals of a cell on open circuit tending to cause a current to flow* (¶ 35).

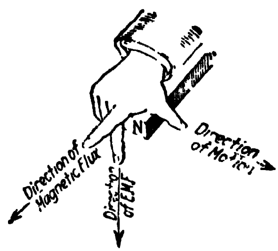


Fig. 278. — Right-hand Rule for Determining the Direction of Induced E.M.F.

259. To Find the Direction of the Induced E. M. F. RIGHT-HAND RULE. *Place the thumb, the first and second fingers of the right hand all at right angles to each other* (*Fig.* 278) *and in such relation to the wire that the first finger points in the direction of the magnetic flux of the magnet, and the thumb in the direction of motion of a wire; the second finger will then indicate the* DIRECTION OF THE INDUCED E. M. F. IN THAT WIRE.

Applying this rule to the wire AB of Fig. 279, which is being moved down past the **N**-pole of the magnet, it is found that the direction of current is *from* B *toward* A. If either the polarity *or* direction of motion be reversed, the current in the wire AB will be reversed. If both the polarity and motion are reversed the current will be in the same direction as in the figure. The student should prove these statements by the above rule.

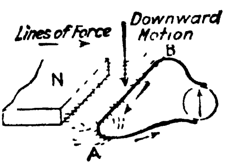


Fig. 279. — Application of Right-hand Rule

Another method of ascertaining the direction of the induced current recalls to mind the direction of the magnetic whirls around a wire which corresponds to the direction of current through it (Fig. 125). If the wire AB (Fig. 279) is moved *downward* across the lines of force which extend from *left* to *right*, the direction of motion is such that if the magnetic lines below the wire were flexible they would tend to wrap themselves around the conductor in an anti-clockwise direction, and if the wire is grasped with the right hand so that the fingers will show the direction in which the magnetic lines are wrapped around the wire, the extended thumb will indicate the direction of current. Since the tendency of the induction is,

in this case, to produce magnetic whirls in a direction which is *anti-clockwise* as viewed along the wire, the current set up will flow toward the reader or from B toward A.

260. Value of the Induced E. M. F. — The magnitude of the induced E. M. F. generated in a conductor when it is cutting lines of force is *proportional* to the rate at which the lines of force are cut. *When a conductor cuts lines of force at the rate of* 100,000,000 *per second, a pressure of one volt is set up between its terminals.*

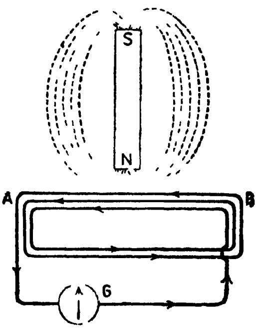


Fig. 280 - Increasing the Induced E.M.F. by Increasing the Number of Cutting Wires.

If a single conductor is moved across a magnetic field, the average number of lines of force cut per second by the conductor would equal the total number of lines of force contained in the field, divided by the time in seconds required to move the conductor across that field. The number of lines of force cut by a wire in one second moving in a magnetic field, therefore, depends upon the strength of the field and the speed at which the wire is moved. The number of lines cut will also depend upon the length of the wire, and upon the angle at which the wire moves across the field (¶ 262). If a wire, AB of Fig. 280, cuts one hundred million lines of force per second, causing a pressure of one volt to be set up between its ends, and there are three similar wires joined in series and moved so as to cut the same number of lines per second as the single wire, three times the pressure would be set up, namely three volts.



Fig. 281. - The Magnetic Polarity Produced in the Coil by the Current tends to Stop the Motion Producing the Current — Lenz's Law.

The induced E. M. F. will, therefore, depend upon the following factors:

(*a*) *The strength of the magnetic field* (*the number of lines of force that it contains*),

(*b*) *The speed of the wire in cutting the flux*;

(*c*) *The number of wires cutting the lines of force.*

Experiment 81. — Connect the student's galvanometer (Fig. 172) to the "secondary coil" (Fig. 281) and using a bar magnet make experiments to verify all the statements given in ¶ 258.

Experiment 82. — With two bar magnets held together to make a compound magnet, and with two coils having different numbers of turns, verify the statements (*a*), (*b*) and (*c*) above.

Experiment 83. — Connect the two ends of a wire about 30 feet long to a galvanometer, and swing slowly as large a portion of the wire as possible around a horizontal axis. Observe the nature of the induced voltage which results from cutting the earth's magnetic field.

Experiment 84. — Connect a cell to the detector galvanometer (Fig. 172) and note whether the needle is deflected to the right or left of zero when the current enters by the right-hand binding post. Having determined the direction of deflection for a particular direction of current through the instrument, substitute for the cell the secondary coil, and repeat the experiments enumerated in ¶ 258. Find the direction of the current in the coil by tracing the direction of the winding, noting the direction of deflection of the galvanometer needle and applying the right-hand rule.

261. Lenz's Law of Induced Currents. When one pole of a magnet is thrust toward a coil, the direction of the current caused by the induced E. M. F. will be such as to make the face of the coil near to the magnet's pole of the *same polarity* as that pole (Fig. 281). Hence, *there is a magnetic repulsion between the magnet and the coil when one is being approached to the other.* When the magnet's pole is withdrawn the *direction* of the *induced current is reversed;* the face near the magnet will now have *opposite polarity* to the pole of the magnet, and consequently *attraction exists* between them. *In each instance the magnetic attraction or repulsion tends to oppose the motion of the magnet.* The above statements are expressed concisely in LENZ'S LAW, as follows:

IN ALL CASES OF ELECTROMAGNETIC INDUCTION THE DIRECTION OF THE CURRENT OCCASIONED BY THE INDUCED E. M. F. IS SUCH THAT THE MAGNETIC FIELD SET UP BY IT TENDS TO

STOP THE MOTION PRODUCING IT. To produce the current in the coil energy must be expended in bringing the magnet to the coil and in taking it away. If the magnet is moved by hand, muscular energy is expended; if attached to the end of the piston rod of a steam engine and moved in and out of the coil, mechanical energy is expended, and a constant but alternating E. M. F. will be produced. It will also be seen that if the coil terminals are open or disconnected very little energy will be required to move the magnet, since there will only be an induced E. M. F. set up, and with no current flowing there will be no attraction and repulsion to overcome. The extra energy required when the coil is closed is expended in producing the current, and it is in this way that *mechanical energy is converted into electrical energy in the electric generator.*

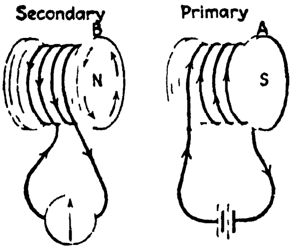


Fig. 282. The Magnetic Polarity Produced in Coil B by the Current Set up in it Tends to Stop the Motion Producing this Current Lenz's Law.

The word *primary* is often used as an abbreviation for *primary coil*. The *primary coil* is the coil producing the induction, or it is the inducing body, while the *secondary coil*, or *secondary*, is the body under induction. In Fig. 281 the bar magnet is the primary body and the coil is the secondary body.

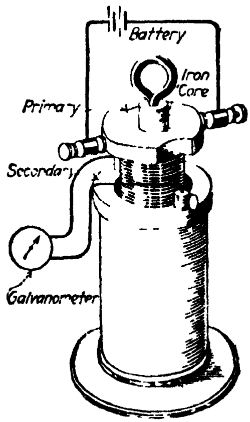


Fig. 283. - Experimental Induction Coil.

Lenz's Law is further illustrated in Fig. 282, where the primary body, A, is an electromagnet with its polarity as indicated. On moving this electromagnet *toward* the secondary coil, B, the induced current flows so as to make the near face of B of **N**-polarity, and *repulsion* results as before. During the *recession* of the primary from the secondary coil the polarity of the secondary is *reversed* and *attraction*

exists, *opposing their separation.* The attraction and repulsion takes place only while the coil is moving. Induced currents may be demonstrated with the induction coil (Fig. 283), which consists of a primary and a secondary coil of copper wire.

The principle may be further illustrated by considering the coils to be stretched out as shown in Fig. 284 at AB and CD. With the key closed in the primary circuit CD magnetic whirls surround the wire, and if the secondary wire AB is moved *toward* CD, it cuts the lines of force of the primary circuit, producing a momentary current during the motion. The direction of this induced current is opposed to that of the primary current; it may be termed an *inverse* current. Verify this statement by the right-hand rule of ¶ 259. If the secondary be moved *away* from the primary, the secondary circuit is again cut by the flux, and a so-called *direct* momentary current is induced. With both circuits stationary, when the switch is closed the magnetic lines of force springing from the primary circuit CD cut the secondary circuit AB, and an *inverse* momentary current flows through the secondary, for the period of time required to establish the field around the primary. When the switch is opened the magnetic lines of the primary will collapse upon it and again cut the secondary, but in the opposite direction, producing a *direct* current. If the primary switch be automatically closed and opened continually, the momentary induced currents will become regular and will change their direction with each make and break of the primary, thus constituting an *alternating current.*

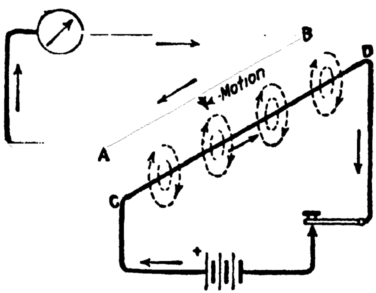


Fig. 284. Inverse Current in Secondary upon Approaching Primary.

When an electromagnet is supplied with an alternating current, the magnetic field will be continually in motion. A secondary coil brought near this electromagnet would be continually cut by the varying flux, and a constant induced al-

ternating current would be obtained, the character of which is like that in the primary circuit. The alternating-current transformer is dependent on this principle (¶ 357).

Experiment 85. — With the student's induction coil (Fig. 283) all of the above cases should be verified and the results noted. To ascertain whether the induced current is a direct or an inverse one the relation between the galvanometer deflection and the current should be determined, as in Experiment 84.

262. Variation of Induced E. M. F. with the Rate of Change of Magnetic Lines of Force. *Faraday's Law.* — To produce induction in a closed coil located in a magnetic field it must be

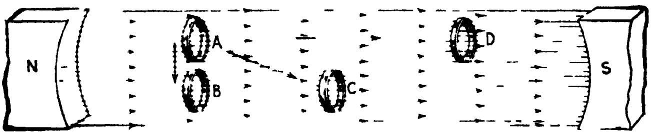


Fig. 285. — No Current is Induced in a Coil when Moved so as to leave Magnetic Lines through it Unchanged.

so moved that the number of lines of force threading through it is constantly changing.

The induced E. M. F. is proportional to the rate of change of the magnetic lines threading through the coil. For example, take the closed coil of wire, A (Fig. 285), located in a *uniform* magnetic field, NS, with its plane at right angles to the lines of force. When the coil is moved vertically downward across the field to position B, magnetic lines of force are cut, but no induction results since the number of lines of force threading through the coil have not been altered. From another viewpoint the upper half of the coil cuts the lines in the *same direction* as the lower half, consequently the direction of the induced E. M. F. in each half is the same, or the E. M. F.'s are opposed to each other, and, being of the same value, no current can flow. If the coil A is held either in a vertical position or at an angle, and then moved across the field in the direction of the arrows to either position C or D, no induction will take place for the same reason.

If the coil be now turned from its vertical position, A (Fig. 286), by say 45° to the position B, *the number of lines of force threading through it will be altered* (decreased), and during the

angular motion an induced current flows around the ring in the direction of the arrow. In this case each half of the coil cuts the lines of force in an opposite direction from the other, consequently the induced E. M. F.'s are also opposite in direction and therefore add to each other, and set up a current which flows around the ring. When moved through the next 45°, or from B to C, the rate of change of magnetic lines through the coil continues, and is greater than when it is moved from A to B. This will be seen by noting the comparative number of lines about coil B, which pass over it instead of threading through it at this angle of inclination, 45°, and have, so to speak, been emptied out. At the position of coil C, all the

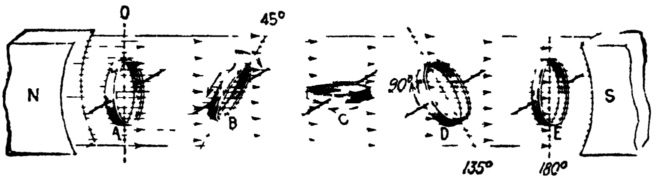


Fig 286 — Phases of Induction in a Closed Coil Rotated in a Magnetic Field Principle of the Generator

lines of force above it have been emptied out of the coil, and the rate of change at this position is a maximum. The induced E. M. F. then varies from 0 in position A, to its maximum value at position C, 90° from A.

If the motion of the loop be continued from C to D, many lines of force will now be included by the coil and induction will occur. The direction of the current, as found by the right-hand rule, is indicated in the figure. The induced E. M. F. gradually decreases during the motion from C to D, because the rate of change in the number of lines of force decreases in the the same ratio as it increased during motion from B to C. Motion from D to E corresponds to that from A to B, and in E all the lines are again flowing through the loop, causing no induction at this position, since there is no change of magnetic flux. During the revolution of the coil through 180°, from position A to E, the E. M. F. gradually increases from 0 to a maximum at 90°, and gradually decreases again to 0 at 180°.

The same will be true of the second half of the revolution 180° to 360°, except that the direction of current is the *reverse*, since moving a conductor up past lines of force produces a current of opposite direction from that obtained when it is moved down past the same lines. When the loop is mounted on a shaft and rotated, it becomes a simple *alternating-current* generator (¶ 276).

Faraday's Law is as follows: LET ANY CONDUCTING CIRCUIT BE PLACED IN A MAGNETIC FIELD; THEN, IF BY A CHANGE IN POSITION OR A CHANGE IN THE STRENGTH OF FIELD THE NUMBER OF MAGNETIC LINES OF FORCE PASSING THROUGH OR INTERLINKED WITH THE CIRCUIT IS ALTERED, AN E. M. F. WILL BE INDUCED IN THE CIRCUIT PROPORTIONAL TO THE RATE AT WHICH THE NUMBER OF LINES IS ALTERED.

Fig. 287 shows how a coil of wire may have an E. M. F. induced in it by moving it without rotation in a *non-uniform* magnetic field. In the position of the coil shown by the solid lines, the number of lines of force through it is less than in the dotted position, consequently an E. M. F. is induced during a movement from one position to the other. The direction of current in the coil is found by the right-hand rule, and is such that if the ring be viewed from the side toward the **N**-pole as it is being moved away from this pole the induced current flows around it clockwise, producing a **S**-pole on this face, with resulting attraction for the **N**-pole from which it is receding.

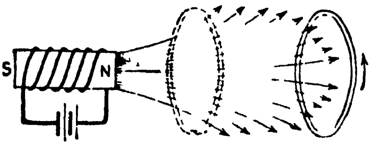


Fig 287. The Induced E M. F Depends upon the Rate of Change of the Magnetic Lines through the Coil — Faraday's Law.

263. Eddy Currents. — When a permanent magnet is supported over a copper disk and the disk is rotated, currents are generated in the disk, which tend to oppose the motion producing them. If the magnet be free to move, it will be dragged around in the same direction that the disk rotates. According to Lenz's Law, the current in that part of the disk moving toward the magnet pole will be in such a direction that a magnetic field is set up of the same polarity as the pole being approached.

therefore tending to repel the magnet, while the current in the receding part of the disk will be in such a direction as to produce a field of the opposite polarity, thus attracting the magnet. Both actions, then, tend to urge the magnet in the same direction and to cause its rotation. If the magnet be held stationary and the disk revolved considerably more force must be applied to turn it than when the magnet is not near it. Each part of the disk, as it comes under the influence of the magnet, is subjected to rapidly succeeding increases and decreases in the number of lines of force threading it.

Such currents induced in masses of metal either by being rapidly cut by the moving field or by moving in the field are called *eddy currents*. The direction of the eddy currents in the copper disk for a particular case is shown in Fig. 288. The magnet is stationary and the disk is rotated clockwise. The currents circulate around the disk in the form of two semi-circles. In the left-hand one the direction is anti-clockwise, producing a **N**-face on the disk which repels the **N**-pole of the magnet, and tends to stop the motion producing it. On the right-hand side a **S**-face is produced, attracting the **N**-pole, and again tending to stop the motion of the disk, according to Lenz's Law. When the magnet is free to move, it will tend to move so that its poles will always be over the unlike poles induced in the disk, but as soon as the magnet moves the paths of the eddy currents also change. They will always be set up with the magnet as their diameter, and each half of the disk will be of opposite polarity to that of the other. The position which the magnet seeks is never attained and continuous rotation results as long as the disk is rotated.

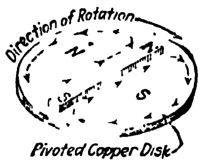


Fig 288. Eddy Currents Induced in a Copper Disk Rotated under a Stationary Permanent Magnet.

If pieces of wire gauze are pressed against the disk directly under each pole of the stationary magnet (Fig. 288) forming wiping contacts, or *brushes*, and the brushes connected to a galvanometer, the needle will be deflected by the eddy currents when the disk is rotated. *Faraday's disk dynamo* consisted of a copper disk rotated between the two poles of a

magnet (Fig. 289), the current being led off from the edge of the disk and returned to the center by brushes. Barlow's wheel (Fig. 164), when rotated by hand, will supply current to an external circuit, illustrating the convertibility of a dynamo.

A compass needle in a metal case will come to rest very quickly, because by its oscillating motion it induces eddy currents in the case which tend to stop the motion of the needle. Eddy currents circulate in the metallic bobbin of the D'Arsonval galvanometer coil when it moves in its magnetic field and these tend to stop the motion according to Lenz's Law. It is for this reason that modern voltmeters and ammeters are so dead-beat. The damping action also takes place in the copper disk rotated between permanent magnets in the Thomson watt-hour meter, ¶ 224.

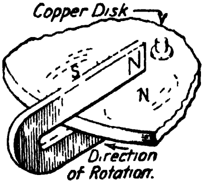


Fig. 289. — Eddy Currents Utilized in Faraday's Disk Dynamo.

The eddy currents circulating in solid conductors are converted directly into heat and are the source of much loss of energy in generators, motors and transformers. To avoid them as far as possible, the solid conductor, such as the iron core of a dynamo armature or transformer, is made up of laminations, the plane of which is parallel to the lines of force of the field. The thinner the laminations the less will be the loss due to eddy currents.

Experiment 86. — Strongly magnetize a bar electromagnet and strike one pole with a piece of flat sheet copper; a cushioning effect will be observed. It is impossible to strike the pole with as great force as when the current is off. Eddy currents are induced in the copper, the reaction of the magnetic field of which tends to oppose the motion. The same is true if the sheet of copper is lifted from the pole quickly.

Experiment 87. Suspend a copper penny by a thread between the poles of a horseshoe electromagnet. Twist up the thread and permit it to unwind. Send a current through the magnet and the motion of the penny will cease, due to the reaction of the eddy currents. When the circuit is broken the thread carrying the penny continues to untwist.

264. Magnetic Hysteresis. — Another source of energy loss in the iron or steel parts of electrical machinery that are subjected to rapid changes in magnetization is called *hysteresis* (pronounced hister-ee'-sis). See ¶ 293.

Experiment 88. — The rapid magnetization and demagnetization of the iron core of an electromagnet, for example by an alternating current, produces heat as a result of the molecular friction between the particles of the iron. Excite an electromagnet from a source of alternating current. If it has a solid iron core it will get quite hot because of the eddy currents induced in it and because of magnetic hysteresis. The cores of alternating-current electromagnets are made of bundles of iron wire to increase their resistance to the flow of eddy currents.

265. Mutual Induction. The induction due to two independent electric circuits reacting upon each other is called *mutual induction*. The previous examples of induction in a secondary circuit due to current flowing in the primary circuit illustrate mutual induction. Parallel conductors carrying independent alternating currents react upon each other by reason of the mutual inductive influence between them. Mutual induction in telephone circuits often gives rise to cross-talk unless the line is so constructed that the induction effects are neutralized (¶ 269).

266. Self-Induction. — *Self-induction* is defined as the cutting of a wire by the lines of force of the current flowing through it. When a current begins to flow along a wire the magnetic whirls spring outward from the center of the wire and cut it. This cutting of the wire by its own lines of force induces in it a momentary *inverse* E. M. F., or an E. M. F. which opposes the applied E. M. F., and it is called a *counter E. M. F.* With a steady impressed electromotive force the induction in a circuit is only momentary, therefore, a brief interval of time must elapse before the current in the circuit reaches its normal value. When the current flowing through the wire is stopped, the magnetic field collapses, and in so doing again cuts the wire, but in the *opposite direction*. A momentary induced E. M. F. is set up which is now *direct*, or in the same direction as the applied E. M. F. The effects of self-induction are, therefore, to oppose the starting of a current by reason of the inverse E. M. F. which must be overcome before the current can reach its full value, and to momentarily retard the cessation of the current by reason of the direct induced E. M. F. when the circuit is broken. Momentary currents of self-induction are also produced in any circuit by any change in

its current strength, whereby the number of lines of force surrounding or interlinked with it is increased or decreased.

The effects of self-induction are very marked in circuits having the form of a helix, for in these circuits the magnetic field of every turn cuts many adjacent turns and the counter E. M. F. is increased, being proportional to *the number of turns and the rate of change of magnetic flux through the coil.* When the coil contains an *iron core* the effects of self-induction are very much greater.

One noticeable effect of self-induction is the bright spark appearing at the point where a circuit, containing wire wound around an iron core, is broken. But little effect is noticed on closing such a circuit on account of the counter E. M. F., but at "break" a spark appears, due to the momentary induced E. M. F which tends to prolong the current in the circuit. The more rapidly the current is brought to zero the greater will be the induced E. M. F. The induced E. M. F. at break is very likely much higher than the applied E. M. F. If the terminals at the point of break of a circuit containing a coil are held, one in each hand, and then separated, the body will receive a shock, the intensity of which will depend upon the size of the coil and the amount of current used. Perhaps no shock will be felt upon placing the hands across the battery in that circuit. These facts indicate that the E. M. F. of self-induction is much higher than the battery E. M. F.

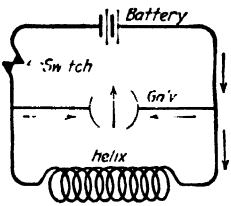


Fig. 290 Experiment Illustrating Self-induction.

Experiment 89. Connect a galvanometer in parallel with a helix of fine wire Fig 290. Close the circuit and the current will divide between the galvanometer and the helix; as a result the galvanometer needle will be deflected, say to the right of zero Move the needle, by hand, back to the zero position, and place some obstacle in the way, so as to prevent it turning again to the right of zero Now release the battery key and a momentary current, due to the self-induction of the helix, will flow through the galvanometer, momentarily deflecting its needle in the opposite direction The induced current through the helix, at break of the circuit, is in the *same direction* as the battery current was, but flows in the opposite direction through the galvanometer connected to it. This is shown by the dotted arrow in the figure.

Experiment 90. — In Fig. 291 an incandescent lamp is connected in shunt with an electromagnet and through a switch to a battery of an E. M. F. equal to that required by the lamp. The resistance of the magnet should be such that with current flowing, the lamp filament is just perceptibly red. At the instant of closing the switch the momentary induced E. M. F. of self-induction opposes the growth of current in the electromagnet, causing most of the current to flow through the lamp, which glows brighter for a moment and then becomes dim as the current attains its steady value in the electromagnet. On opening the key the lamp again flashes brilliantly since it is still in circuit with the electromagnet. The energy stored in the magnetic field is thus converted into a momentary direct current which illuminates the lamp.

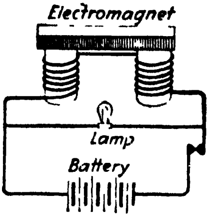


Fig. 291. — Experiment Illustrating Self-induction.

The field coils of a dynamo should not be broken when fully excited since the E. M. F. of self-induction may become so high as to cause a puncture of the insulation at two or more points and thus complete the circuit through the iron core, and cause a ground. The self-induction at the break of such a circuit is termed the *field discharge*. Sometimes multi-blade switches are used in field circuits so that they may be opened simultaneously at a number of places, thus reducing the danger of breakdown of the insulation.

267. The Spark Coil. The spark produced when a coil is open-circuited is utilized to ignite the gas in an electric gas lighting system and in the ignition system of a gas engine. Such a *spark coil* consists of many turns of low-resistance insulated copper wire wound upon an iron core to form a single winding, the length of the core and the number of turns of wire depending on the use to which the coil will be put. The core is not solid, but consists of a bundle of soft iron wires in order to decrease the eddy currents. The construction of the coil is shown in Fig. 292. The E. M. F. developed in the coil when the current ceases to flow is due to the collapsing magnetic flux cutting the turns.

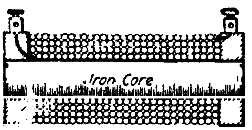


Fig. 292. — Spark Coil in Cross-section.

268. Inductance. — The cause of the self-induction is due to the property possessed by a wire or coil called *inductance*, which is a measure of the amount of magnetic flux which may be associated with the electric circuit. A coil or wire possesses inductance whether current is passing through it or not. The amount of inductance offered by a coil depends on the number of turns of wire in the coil and on the magnetic conductivity of the medium surrounding it. A coil of 50 turns wound around an iron core has a much higher inductance than a coil of 50 turns without an iron core. A coil of 15 turns wound on an iron core has less inductance than one of 60 turns on a similar core.

The inductance of a coil or circuit is measured by the E. M. F. induced in it when the current varies at any given rate. The unit of inductance (the symbol for which is L) is called the *henry*, and is the inductance of a circuit in which the induced E. M. F. is one volt when the current through the circuit varies at the rate of one ampere per second. Thus, if the current in a circuit varies at the rate of 10 amperes per second and induces an average of 120 volts, the inductance of that circuit is 12 henrys. The secondary coil of a 2-inch spark coil has an inductance of about 50 henrys; a 2.5-ohm electric bell has 0.012 henry or 12 millihenrys; the field coils of a certain 3.5-kw., 110-volt, shunt-wound dynamo has 13.6 henrys.

The inductance of an air-core solenoid of average radius r inches, of length l inches and of n turns of wire is approximately

$$\text{Inductance } L = \frac{n^2 \times r^2}{l} 10^{-7} \text{ henrys} \quad . \quad . \quad \textbf{(100)}.$$

Thus a coil of 1000 turns formed into a solenoid 10 inches long and 2 inches average radius would have an inductance of $1000 \times 1000 \times 2 \times 2 \div (10 \times 10^7) = 0.04$ henry.

With a direct current flowing in a circuit containing inductance, there is no inductive action after a steady flow of current has been established, which usually requires only a fraction of a second. In this case the inductive action is only momentary, that is, at the instant of closing the circuit, and upon breaking the circuit. With an alternating current, however, since the current is continually varying in value, the effect of self-induction will continue as long as the current is main-

tained and will greatly reduce the flow of current in the circuit.

269. Neutralizing the Effects of Self-Induction. – *Inductive and Non-Inductive Circuits.* Self-induction in a coil may be neutralized by winding one-half of the wire in a right-hand direction and the remainder in the opposite direction. This is accomplished in practice by folding the length of wire to be used at its middle point and starting at this point, winding both halves at the same time as a single wire until the terminals are reached. The magnetic effect of the current flowing in one direction neutralizes that of the same current flowing in the opposite direction, and the coil is said to be *non-inductive*, while an ordinarily-wound coil constitutes an *inductive circuit*. No polarity would result from inserting an iron core in a non-inductively wound coil since the current through one-half of the

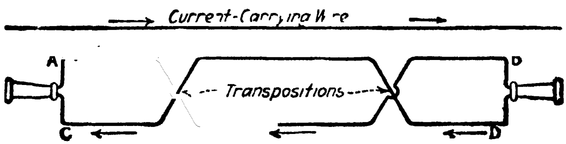


Fig. 293. - Transposition of Telephone Lines to Eliminate the Mutual Induction by Neighboring Wires

turns would tend to magnetize the core oppositely to that through the other half.

An incandescent lamp is practically a non-inductive resistance, while an electromagnet is an inductive resistance. The coils of laboratory rheostats and Wheatstone bridges are wound non-inductively, so that they will have no magnetic influence on a galvanometer, and also so that the currents in the bridge arms may reach their maximum values simultaneously.

Mutual induction between parallel wires in the same circuit is reduced by running the wires as close together as possible. Mutual induction also occurs between two parallel circuits, as for example in telephone wires running close to electric lighting, street railway or power lines, which carry relatively heavy currents fluctuating in value. These lines set up induced currents in the telephone circuit close to it, rendering the telephone cir-

cuit "noisy." Such inductive disturbances are due to electrostatic as well as to electromagnetic induction, and may be eliminated by transposing the telephone wires as shown in Fig. 293. Here the "current-carrying wire" represents an electric lighting or power line running near and parallel to the telephone line wires which are shown transposed.

The effect of transposing the wires is to make the average distance between the inducing wire and each side of the telephone circuit the same so that the total E. M. F. developed by electromagnetic induction in wire AB will exactly equal the total E. M. F. induced similarly in wire CD. Hence, the E. M. F. induced in one telephone wire will neutralize that induced in the other and thus eliminate noise in the telephone receiver. The induction between two or more parallel telephone circuits may be detected by the faint sound of voices in the receiver, causing what is termed "cross-talk." The "twisted pair" wire generally used for telephone circuits is an example of transposed wires and effectively eliminates mutual induction in such circuits. Electrostatic induction is described in ¶ 377.

270. Principle of the Induction Coil. An induction coil or Ruhmkorff coil consists of a straight core, made up of a bundle of soft iron wires, around which is wound the cylindrical primary coil, composed of several layers of coarse wire, while a secondary coil composed of thousands of turns of fine wire is wound over the primary. The primary coil is connected to a battery through an automatic interrupter or vibrator (Fig. 294). At the "make" and at the "break" of the primary circuit an E. M. F. is induced in the secondary due to the changing magnetic flux threading through the secondary, and this high induced E. M. F. produces a series of sparks capable of passing through several inches of air from one secondary terminal to the other. The connections of such a coil are shown in Fig. 294, and its general appearance in Fig. 295.

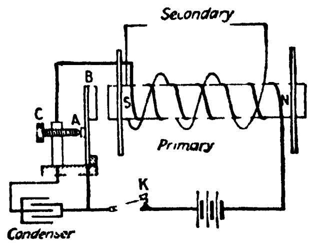


Fig. 294 Diagram of Connections of an Induction Coil.

The interrupter or vibrator is a strip of spring brass or steel fitted at one end with a soft iron armature B, and on the opposite side near its center with a piece of platinum A; the latter is in contact with a platinum-tipped adjustable thumb screw C, when the battery circuit is open at K. When the battery circuit is closed at K, the current flows from A to C, through the primary winding and back to the battery. The instant the current flows through the primary coil it strongly magnetizes the iron core, NS, which core attracts the armature B and breaks the contact of the vibrator with screw C. This breaks the primary circuit, the magnetism of the core ceases, and the vibrator springs back again, "making" the circuit, so that the same events are repeated. The strip of spring metal vibrates continually as in an electric bell, and the circuit is "made" and "broken" hundreds and perhaps a thousand times per minute. An *inverse* induced current in the secondary corresponds with each "*make*" of the primary, while a "*direct*" current is induced on each "*break*" of the primary. Interrupted currents in the primary, therefore, produce alternating currents in the secondary.

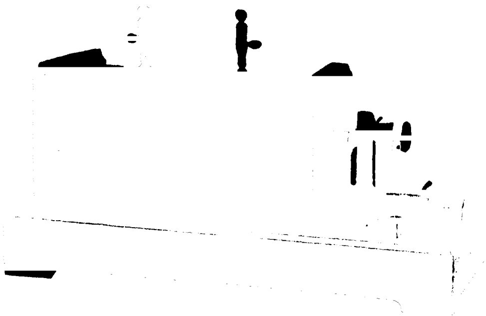


Fig 295. Induction Coil.

The *self-induction of the primary circuit* has a very important bearing upon the action of the coil. At "make" of the primary the counter E. M. F. opposes the battery current, and prevents the magnetic flux from rising rapidly in the core, while at "break" the self-induced current in the primary tends to prolong the primary current, preventing its rapid fall to zero by sparking across the contacts. *A rapid rate of magnetization and demagnetization of the iron core means a great rate of change of the magnetic flux threading through the secondary coil, and, hence, a high E. M. F.* *A condenser* (¶ 271) is added for the

purpose of suppressing this spark across the primary break and of aiding the primary current to fall abruptly to zero.

Experiment 91. — The primary and secondary coils, illustrated in Fig. 283, may be mounted on a base and equipped with a contact screw and vibrator, so as to form an induction coil similar to that shown in Fig. 295. Using the primary alone, the automatic action of the electric bell is illustrated, and when the secondary is introduced, the induced electromotive forces therein may be demonstrated. When short lengths of brass tubing are attached to the secondary terminals of a small induction coil and then clasped, one in each hand, a peculiar muscular contraction is produced, due to the high voltage of the induced E. M. F. This demonstrates the physiological effect of an electric current. This experiment should not be attempted with coils capable of producing even short sparks in air between their secondary terminals.

271. Action of the Condenser. A condenser for an induction coil consists of two sets of interlaid layers of tin foil separated by sheets of paper coated with paraffin or a mixture of beeswax and rosin (Fig. 296). The alternate layers of tin foil are connected to each other, and two common terminals are thus formed, as depicted in Fig. 297. There is no electrical connection between the condenser terminals, but if they are connected to a source of E. M. F. the plates become electrified or charged, after which they may be discharged when a proper path is afforded. The condenser is located in the base of the coil shown in Fig. 295, and its terminals are connected across the primary break, points A and C of Fig. 294.

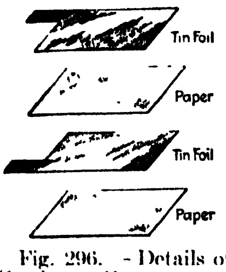


Fig. 296. - Details of Condenser Construction.

The condenser action is as follows: when current flows through the primary at "make" (Fig. 294), no energy can be stored up in the condenser because it is short-circuited by the contacts. At "break" the E. M. F. of self-induction in the primary, instead of overcoming the resistance across the contacts, charges the condenser. At "break" also there is a complete circuit for the condenser back through the battery and the primary coil, through which a discharge takes place in the *opposite direction* to that of the primary current; the condenser thus aids in quickly demagnetizing the iron core by tending to set up magnetic flux

in the opposite direction. If the primary circuit is again completed before the *reverse condenser current* disappears, as is practically the case, the condenser is short-circuited by the contacts and the remaining charge is quickly dissipated. In consequence, the primary current can be quickly brought to zero; this means a rapid decay of magnetic flux and a high secondary E. M. F. Since the primary current (and thereby the magnetic flux) cannot rise nearly as rapidly as it decays because of the condenser, the secondary discharge *becomes practically an intermittent current of high voltage in one direction only*. In medical induction coils where no condenser is used the secondary charges are more nearly equal.

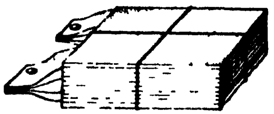


Fig. 297. — Plates of a Condenser Assembled and Connected.

Experiment 92. – Using an induction coil capable of producing sparks two inches long or longer in air, observe that the length of spark produced on the "break" exceeds that on the "make." When the gap length is such that sparks pass only on the "break," note the bright part of the spark near one terminal; this is the *negative* terminal.

Experiment 93. Connect a telephone condenser in series with a suitable galvanometer across 110-volt direct-current service mains, using series resistance for protection if desired. Then disconnect it from the mains and join the condenser terminals to the galvanometer only. Observe the direction and nature of its deflection. A double contact key is desirable for making the connections conveniently so that the charge will not be dissipated.

272. Construction of Induction Coils. Induction coils may be divided, according to their use, into two general classes: medical or therapeutic coils, and jump-spark coils. In the former, the secondary winding has a lower number of turns of wire than the secondary of an induction coil intended for producing sparks, so that its E. M. F. is lower, and can be impressed upon the human body. Some means for varying the intensity of the shock is provided, such as altering the number of turns in circuit in the secondary coil by a selector switch, Fig. 298, or by so constructing the secondary that it may be gradually withdrawn from the primary, or by varying the position of a brass tube inclosing the iron core. In the latter arrangement the tube acts as a short-circuited secondary winding and has eddy cur-

rents induced in it; it therefore takes energy from the regular secondary winding and weakens the latter.

The iron core is composed of a bundle of soft charcoal-iron wires, about No. 22 gage. For medical coils the number of layers in the primary is generally from 4 to 6 and the size of wire used No. 24, 22, or 20 B. & S. gage, according to the dimensions of the coil, while the secondary is usually wound with No. 34 or 36. The self-induced E. M. F. of the primary may also be utilized by connecting the "shocking" electrodes across the point of "break" of the current in the primary, as shown at P_1 P_2 in Fig. 298. This results in a lower voltage than that available when the electrodes are connected to the secondary terminals S_1 S_2.

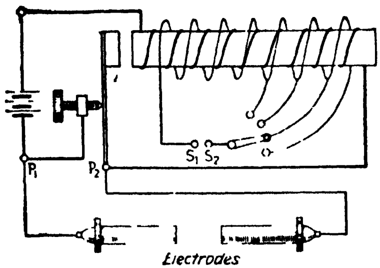


Fig. 298 Connections of Medical Coil

Jump-spark coils are usually rated according to the number of inches that the spark will jump between the secondary terminals through the air. The primary is wound with about two layers of insulated copper wire, usually from No. 10 to No. 16 B. & S. gage, thoroughly insulated from the core, and from the secondary. The secondary is wound over the primary and consists of many turns of copper wire which may range in size from No. 30 to No. 40.

When the coil is designed to produce a spark over 1.5 inches, the secondary should be wound in a number of sections separated from each other by proper insulation. In Fig. 299 the secondary is wound in seven sections in order to reduce the potential between the ends of each, the coils being separated by paper rings as shown. The sections must be so connected that the current will circulate through all of them in the same direction. A certain 12-inch induction coil has 64 sections $\frac{1}{8}$ inch wide in its secondary winding which aggregates 77,400 turns of No. 33 B. & S. gage single silk insulated wire, the average inside diameter being 5 inches and outside being $6\frac{3}{4}$ inches. The primary

of this coil has 2 layers of No. 11 B. & S. gage cotton-covered wire wound to an axial length of $20\frac{1}{2}$ inches over an iron core $2\frac{3}{8}$ inches in diameter. A hard-rubber tube $3\frac{3}{4}$ inches in outside diameter and having a wall $\frac{3}{4}$ inch thick is part of the insulation between the two windings.

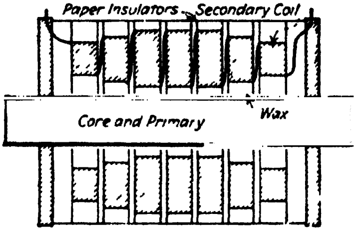


Fig. 299. Multi-coil Secondary of Large Induction Coil.

The voltage generally applied to the primary of the ordinary induction coil varies from about 4 to 25 volts, according to the size. A higher voltage causes excessive sparking and destruction of the platinum contacts. Specially constructed independent vibrators are used with large coils which can be connected directly to an electric-light circuit of 110 volts or more. Such a vibrator is practically a relay, which makes and breaks the current in the independent primary circuit by means of another pair of platinum contact points. This circuit can also be supplied from a 110-volt circuit and the current regulated by a rheostat.

The following table gives the sparking distance and approximate corresponding sinusoidal E. M. F. between opposed sharp needle points under ordinary atmospheric conditions:

Table XIX. Sparking Distances in Air

Volts	Distance (inches)	Volts	Distance (inches)
5,000	0 22	60,000	4 65
10,000	0 47	70,000	5 87
20,000	1 00	80,000	7 1
30,000	1 62	100,000	9 6
40,000	2 44	130,000	12 9
50,000	3 55	150,000	15 0

Interrupters for making and breaking the primary circuit of an induction coil may be *magnetic*, *electrolytic* or *mechanical*. The ordinary interrupter placed on many coils represents the

magnetic method, and though called a "vibrator" (¶ 270), it is in fact a magnetic interrupter.

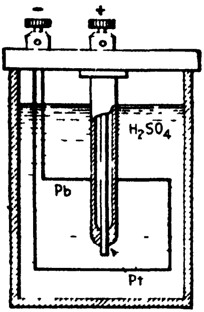


Fig. 300. Wehnelt Electrolytic Interrupter.

The electrolytic or Wehnelt interrupter, a simple form of which is shown in Fig. 300, consists of a glass or porcelain jar containing a dilute solution of sulphuric acid, H_2SO_4, in which is immersed a large lead electrode, Pb, and a small platinum electrode, Pt. The platinum is introduced into the electrolyte through a glass tube, the platinum being so arranged as to present a very small area, practically a point, to the electrolyte. If these two electrodes are connected in series with the primary of an induction coil in such a manner that the platinum is connected to the positive terminal of the source of supply, the current in the circuit will be subjected to regular and very rapid interruptions. The current flowing through the electrolyte from the platinum to the lead plate sets up electro-chemical action liberating gases; the oxygen enveloping the platinum tip insulates it from the solution, thereby opening the primary circuit. The flow of current having been stopped, there is nothing to sustain the gas bubbles, which accordingly collapse, allowing the current again to flow through the primary, after which the above action is repeated indefinitely The action is very rapid and the interruptions are sharp. The speed of the interrupter depends upon the area of the platinum exposed, the inductance of the coil, and the voltage. This type of interrupter will not function well on continuous potentials of less than 80 volts.

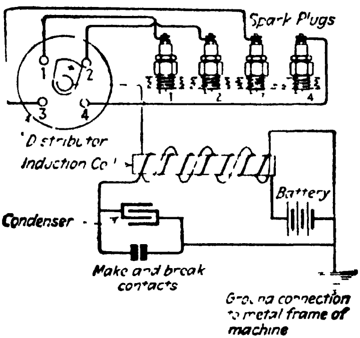


Fig 301. — Connections of Automobile Ignition Coil.

A mechanical interrupter is any device that will open and close two contact points by means of a purely mechanical contrivance, such as the contact wheel or "breaker" (sometimes called the "timer") that is used in connection with the ignition systems on automobiles (¶ 273), and the mercury jet interrupter.

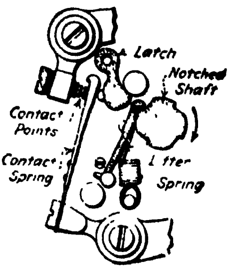


Fig. 302. — Contact-maker for Ignition System.

273. Induction Coils for Automobile Ignition Systems.- Induction coils used to produce the spark in the ignition systems used on automobiles have a primary and secondary winding and are equipped either with a vibrator (or magnetic interrupter) or with a mechanical device for interrupting the current flowing through the primary from a battery or low-voltage magneto. The connections of the induction coil with a mechanical interrupter, the "spark plugs" and the distributor, as used in connection with a typical automobile ignition system, are shown in Fig. 301.



Fig 303. — External View of Remy Contact-maker and Distributor for Automobile Ignition System.

In Fig. 302 is shown the contact-maker, which consists of a notched shaft (having one notch for each cylinder of the engine) rotating at one-half the engine speed, a lifter or trigger, which is pulled forward by the rotation of the shaft, a spring which pulls the lifter back to its original position, a hardened steel latch and a pair of contact points. The contact points are shown open, the lifter being pulled forward by the notched shaft: when pulled forward as far as the shaft will carry it, the lifter is suddenly pulled back by the recoil of the spring. In returning, it strikes against the latch, throwing this against the contact spring, thus closing the contact for a brief

instant and allowing a current to flow for this instant through the primary winding of the ignition coil. The contact soon thereafter is suddenly broken when the lifter slips into the next notch, and at this instant a high voltage is set up in the secondary. This high voltage is conveyed to the spark plug terminals in the order of firing by the rotating distributor brush (Fig. 301), one terminal of the secondary winding of the ignition coil being connected to this distributor brush, the other secondary terminal being *grounded*, that is, connected to the frame of the engine.

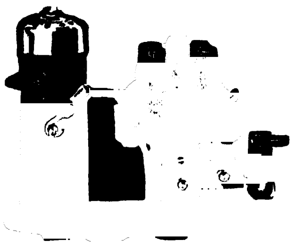


Fig. 304. Atwater-Kent "Unisparker" Magneto Replacement Unit.

The points of the contact-maker are timed to break the circuit just at the instant when the spark is needed in each cylinder, at the same time the distributor brush makes contact with the metal button connected to the spark plug in this cylinder. Fig. 303 shows the external appearance of the Remy ignition distributor and contact-maker, which are operated by a single rotating shaft geared to the engine. Means are provided for advancing and retarding the spark by shifting the contacting plate through a system of levers which terminate on the quadrant of the steering wheel. An external view of an Atwater-Kent "magneto replacement unit," for use on cars having an electric generator and storage battery, is shown in Fig. 304. It consists of the combined distributor and contact-maker on the right and the induction coil on the left, both being mounted into a compact unit that can be attached to the engine in place of a magneto.

QUESTIONS

1. What is meant by electromagnetic induction?

2. If a permanent magnet is placed inside a coil of wire, and if then the terminals of the coil are connected to a galvanometer, will the needle of the instrument be deflected? Give a reason for your answer.

3. In Question 2, after having connected the galvanometer to the coil, suppose the magnet were withdrawn from the coil, in what direction

would current flow around the coil as viewed from the end from which the magnet was withdrawn?

4. How long does an induced current last?

5. How would you determine the direction of the induced E. M. F. in a wire that is moved past one of the poles of a magnet?

6. What determines the value or magnitude of an induced E. M. F.?

7. Why is more force required to thrust a magnet inside a coil when the coil terminals are connected together, than when the terminals are not connected so as to form a closed circuit?

8. How many lines of force must be cut by one conductor per second to generate one volt?

9. State Lenz's Law.

10. How may a conducting circuit be moved across a magnetic field so that there will be no current induced in it? Illustrate your answer.

11. What are eddy currents and of what use are they?

12. Explain what is meant by mutual induction, and self-induction.

13. What is inductance?

14. How may the effect of self-induction be neutralized in coils of wire?

15. How is the effect of mutual induction between parallel circuits neutralized?

16. Calculate the inductance of an air-core solenoid having 2000 turns, a length of 20 inches and a mean radius of 1 inch. *Ans.* 0.02 henry.

17. What E. M. F. is induced in the coil of the preceding problem if the current through it drops uniformly from 25 amperes to zero in 0.01 second? *Ans.* 50 volts.

18. What is the difference between the current flowing from a battery and that from the secondary of an induction coil?

19. An interrupted current in the primary of an induction coil produces an alternating current in the secondary circuit. Explain fully how one secondary terminal can then be called a cathode and the other an anode.

20. Make a complete sketch of an induction coil with condenser, and indicate the directions of current in the primary and secondary circuits at "make" and at "break."

21. What is the advantage of using a condenser with an induction coil?

22. What is the objection to using a solid iron core in constructing an induction coil?

23. Describe and explain the operation of an automobile ignition system.

LESSON XXIII

PRINCIPLES OF DYNAMO-ELECTRIC MACHINES

Dynamos — Classification of Generators — A Simple Generator — Alternating-Current Generator — Graphic Representation of an Alternating Current — Magneto Alternator — Simple Direct-Current Generator — Graphic Representation of a Direct Current — Multi-Coil Armatures — Principle of the Motor — Direction of Rotation of Motors — Questions.

274. Dynamos. The term *dynamo* is applied to machines which convert either mechanical energy into electrical energy or electrical energy into mechanical energy by utilizing the principle of electromagnetic induction. A dynamo is called a *generator* when mechanical energy supplied in the form of rotation is converted into electrical energy. When the energy conversion takes place in the reverse order the dynamo is called a *motor*. Thus a dynamo is a reversible machine capable of operation as a generator or motor as desired.

A generator does not create electricity, but generates or produces an induced electromotive force, which causes a current to flow through a properly insulated system of electrical conductors external to it. The amount of electricity obtainable from such a generator is dependent upon the mechanical energy supplied. In the circuit *external* to a generator the E. M. F. causes the electricity to flow from a higher or positive potential to a lower or negative potential, just as water flows from a higher to a lower level. In the *internal circuit* of a generator the E. M. F. causes the current to flow from a lower potential to a higher potential, just as water is pumped or forced from a lower to a higher level. The action of a generator is based upon the principles of electromagnetic induction discovered by Faraday, and fully considered in Lesson XXII.

The dynamo consists essentially of two parts: a *magnetic field*, produced by electromagnets, and a number of loops or coils of wire wound upon an iron core, forming the *armature.* These parts are so arranged that the number of the magnetic

lines of force of the field threading through the armature coils will be constantly varied, thereby producing a steady E. M. F. in the generator or a constant torque in the motor.

The general appearance of a direct-current dynamo is seen from Fig. 305, which shows a Type K Allis-Chalmers machine A disassembled view of this dynamo appears in Fig. 306, wherein the principal parts are more clearly seen.

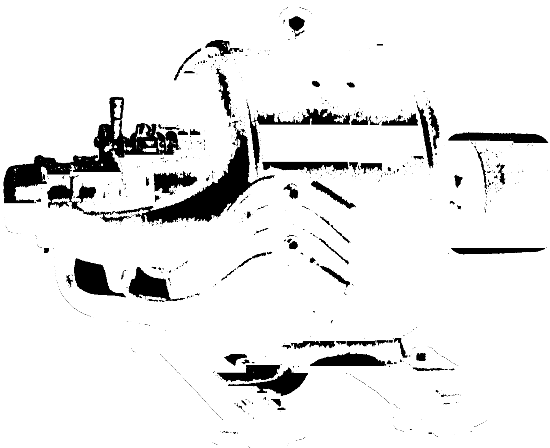


Fig. 305. — Multipolar Motor or Generator.

275. Classification of Generators. - According to their mechanical arrangement, generators may be divided into three classes:

1. *A stationary field magnet and a revolving armature,*
2. *A stationary armature and a revolving field magnet,*
3. *A stationary armature and a stationary field magnet, between which is revolved a toothed iron core.*

In the first class provision is made for conducting the current from the armature either by collector rings (¶ 277) or by a commutator (¶ 280). In the second class provision is made for conducting the current to the revolving field by collector rings, while in the third class there are no moving wires nor contacts.

Generators may be further classified according to their design and mechanical construction into

1. *Direct-current generators,*
2. *Alternating-current generators, or alternators.*

In direct-current dynamos the field magnets are usually stationary while the armature revolves (Figs. 305 and 306). In alternators, the armature is usually stationary, while the field magnets revolve (Fig. 307); while in some types both are stationary while an iron core is revolved. All generators are



Fig. 306. — Dismantled View of Dynamo.

fundamentally alternators — that is, machines in which alternating currents are generated. When provided with a suitable commutator, the current from such a machine is made unidirectional in the external circuit, but still alternates in direction in the armature coils.

A dynamo having only one **N**-pole and one **S**-pole in its field structure is called a *bipolar* dynamo. Those having more than two poles, such as 4, 6, 8, etc., are called *multipolar* dynamos. Modern motors and generators with stationary fields have their field frames constructed in ring form, as shown in Fig. 306, whether bipolar or multipolar. Some experimental bipolar machines are constructed as illustrated in Figs. 309 and 312. Bipolar dynamos are seldom used at the present time except in very small machines and in some large generators that are driven at high speed by turbines.

The use of more than two poles brings with it the advantage of slow speed in the generation of commercial voltages. Slow speed is an advantage in any apparatus with moving parts, because there is less liability of derangement, less wear, and hence less need of renewal of such parts. If a two-pole generator is required to run at 1000 revolutions per minute to generate an E. M. F. of 125 volts, then under otherwise equal

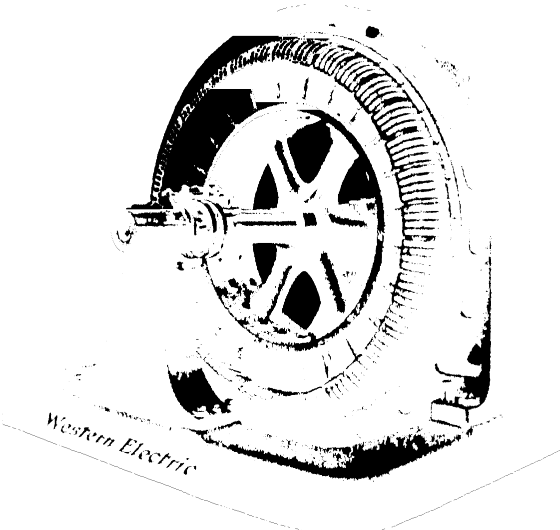


Fig. 307. — Waterwheel-driven Alternator with Revolving Field.

Field coils are of copper ribbon wound edgewise.

conditions a four-pole dynamo of equal voltage need run at only 500 revolutions; one of eight poles, at only 250 revolutions per minute. In subsequent discussions of generator action bipolar fields will be assumed in many cases because of greater simplicity.

The field magnet cores are cylindrical or rectangular in form and usually constructed of cast "mild" steel (soft steel) containing a very small percentage of carbon, the magnetic quality of which is nearly equal to that of wrought iron. This

is a much cheaper construction than where they are forged from wrought iron. These cores are cast-welded into the plain cast iron or cast steel field ring, which, in the larger sizes, is generally divided into two parts, for convenience in handling. The pole faces or shoes are generally constructed of laminated sheet steel, and in some machines the entire field cores are so made.

276. A Simple Generator. — Consider the single closed loop of wire, ABCD of Fig. 308, which is mounted on a shaft and may be rotated by hand around its horizontal axis in the uniform bipolar magnetic field, NS, in the direction of the arrow. The direction and variation in magnitude of the induced E. M. F. is the same as that given under Faraday's Law for the different positions of a loop during a complete revolution in Fig. 286 and ¶ 262.[1] At the position ABCD (Fig. 308), there is no E. M. F. induced in the loop, since all the lines of force of the field thread through it. During the first quarter of a revolution, the lines of force threading through the loop are gradually diminished at an increasing rate, and the E. M. F., *depending on the rate of change of the lines of force* through it, increases in magnitude with its direction from b to a in the right-hand side of the loop, and from c to d in the left-hand side. After it has revolved one-quarter of a revolution to the position indicated by a b c d, the plane of the loop is parallel to the lines of force, so that none thread through it; the rate of change is now a maximum, as is also the E. M. F.

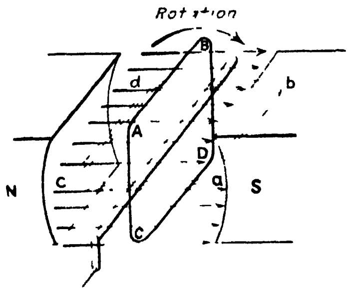


Fig. 308. – Direction and Magnitude of the Induced E. M. F. in a Generator

During the second quarter of the revolution the lines of force thread through the opposite side, which is equivalent to a further diminution of the lines of force through it, the rate

[1] The student is advised to read again ¶ 262, which fully explains the fundamental principle of the generator.

of change and the E. M. F. decreasing until at half revolution the E. M. F. is zero. The direction of the E. M. F. is the same throughout this half revolution, and the current flows around the loop from a to c, to d, to b, to a, changing in strength with every variation of the generated E. M. F. During the next half revolution the same variations in E. M. F. occur but the induced E. M. F. is in the opposite direction. The current is therefore reversed *twice in every revolution*, or *an alternating current flows around the loop.* Fig. 309 shows an Evans experimental machine for illustrating the generation of E. M. F.'s by coils of wire revolving in a magnetic field. The parts illustrated belong to an electrodynamic equipment supplied by the Central Scientific Company.

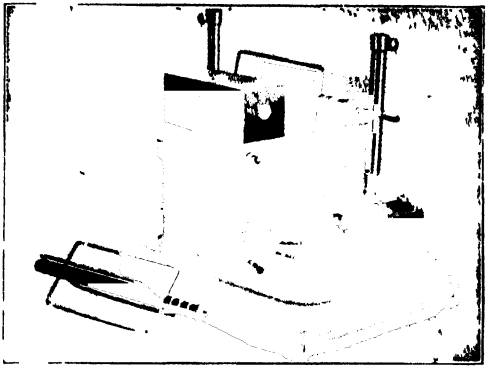


Fig 309 – Generation of an E.M.F by the Rotation of Coils in a Biploar Magnetic Field.

The field magnets are excited from a source of current and the terminals of the coil may be connected by brushes and lead wires to a voltmeter

277. Alternating-Current Generator. — To utilize the current flowing in the foregoing closed loop when it is rotated in the bipolar magnetic field, some mechanical device must be used to lead or collect the current from the rotating loop so that it will flow through a circuit external to it. Two collector rings are used for this purpose and consist of metal rings mounted on wooden or hard-rubber hubs (Fig. 310), these being mounted on the shaft with the loop. The rings *are insulated from each other and from the shaft.* The terminals of the loop are connected, one to each ring, and stationary strips of copper, P and M, termed *brushes*, rest upon the rings and are connected to the external circuit. When the loop is re-

volved a sliding or wiping contact is established and the current is conducted to the *external circuit.*

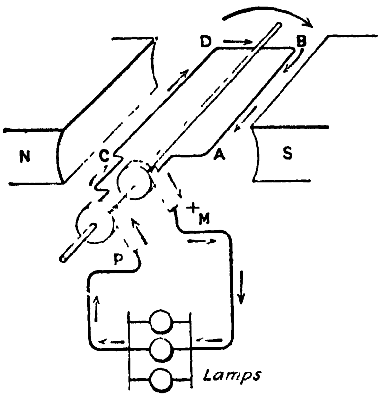


Fig. 310. — Simple Alternating-current Generator.

At the instant depicted in the revolution brush M is positive.

During one half of the revolution of the loop, ABCD of Fig. 310, the direction of current in AB is from B toward A, and *from brush* M, *which is therefore positive,* to the external circuit, composed of incandescent lamps in parallel. From the lamp terminals the current flows back to *brush* P, the *negative brush,* and around the loop from C to D, to B, etc. Now consider the second half revolution depicted in Fig. 311. The direction of current in the wires AB and CD is reversed (right-hand rule) and current flows from D to C, through *brush* P, *now positive,* then through the lamps in the opposite direction to that in Fig. 310, and through *brush* M, *now negative,* to AB, to D, etc. In every revolution of the coil in a bipolar field the polarity of the brushes changes twice, or there are *two alternations of current per revolution in the external circuit.* The number of alternations per minute in any alternator equals the *speed in revolutions per minute multi-*

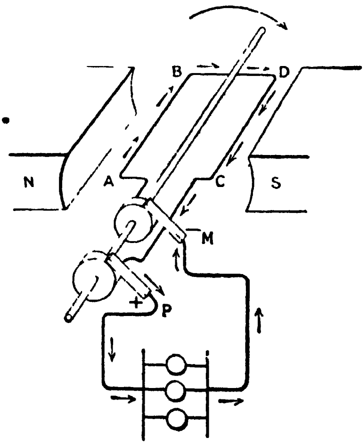


Fig. 311. — Simple Alternating-current Generator.

Direction of current in coil at one-half revolution from the position in Fig. 310; brush M is now negative.

plied by the number of poles. The number of times that one of the brushes becomes positive in one second is expressed as the *frequency*; thus a frequency of 60 means that during each second one brush is positive sixty times and also negative sixty times — in other words the frequency of the current is 60.

Student's Experimental Dynamo. — A simple apparatus for studying the principles of induction and current collection in a dynamo is illustrated in Fig 312, and consists of a horseshoe electromagnet fitted with cast-iron pole pieces and mounted on a wooden base A rectangular coil of No 26 copper wire, having 5 ohms resistance, is mounted on a shaft, suitably supported by a brass framework extending from the pole pieces The framework also carries two insulated brush holders At one end of the shaft the coil terminals are connected to a pair of collector rings mounted upon it, while the same terminals are also connected to a two-part commutator at the other end of the shaft By reversing the position of the coil between the pole pieces the brushes will rest either upon the rings or upon the commutator The electromagnets have a resistance of 1 3 ohms each and are to be excited from a source of direct current. The brushes may be connected to a detector galvanometer, and when the shaft is rotated by hand either the alternating or direct current may be studied When connected as a shunt motor the rectangular coil will attain a speed of several hundred revolutions per minute with an applied E M. F. of 4 volts

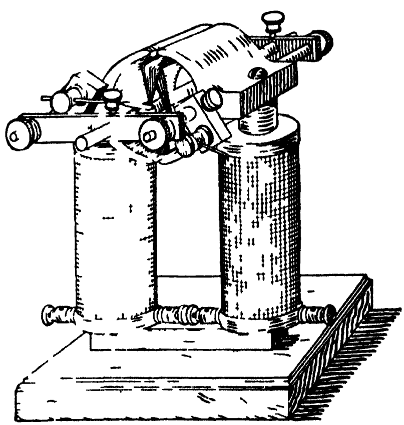


Fig 312 — Student's Experimental Dynamo

Experiment 94. — Separately excite the magnets (connected in series) of the student's experimental dynamo, Fig 312, so that one pole piece will be **N** and the other **S,** and adjust the brushes so that they will bear lightly upon the *collector rings* Connect the brushes to the detector galvanometer, Fig 172

(a) Revolve the shaft slowly and note the alternating deflection of the galvanometer needle

(b) Increase the speed and note that the needle remains at zero with a perceptible vibration.

(c) Turn the coil to the vertical position, break the field circuit and note the galvanometer deflection; close the field circuit and again note the deflection. Why are the deflections opposite?

(d) Reverse the polarity of the fields and repeat (c), noting results.

(e) Turn the coil so that it is horizontal; then make and break the circuit. The galvanometer needle is not appreciably deflected. Why is this so, in view of the fact that this is the position of maximum induced E. M. F. of a loop rotated in a bipolar field? Why is it different in this case?

278. Graphic Representation of an Alternating Current. — The changes in direction and magnitude of an alternating current are frequently represented diagrammatically. For example, suppose a current of 5 amperes to flow for one second in one direction, and then be automatically reversed and flow for one second in the opposite direction, and reversed again, this *cycle* of events continuing at regular intervals while the current flows. The action is represented in Fig. 313, where the horizontal line, PK, is divided into equal distances, PC, CF, FK, etc., each representing one second of time. The vertical line, AM, at right angles to PK is divided into distances representing units of current, the current is said to flow in a positive direction when indicated above PK, and negative when below PK. When the switch is closed the current is seen to rise to its full strength of 5 amperes, or from P to A, and 5 amperes are maintained constant in a positive direction for one second. A to B. When point B is reached at the end of the first second the current falls abruptly to zero, B to C, and rises to 5 amperes in a negative direction, and is maintained for an equal interval of time, D to E, when it again falls to zero at F, and repeats the same cycle of events in equal intervals of time. The line PABCDEFGHK is called the *wave form* of an alternating current.

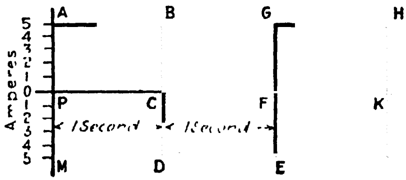


Fig. 313. — Graphical Representation of an Alternating Current.
Wave shape is rectangular

In Fig. 313 the current is depicted as being of constant

strength during each second, while it was shown in ¶¶ 262 and 276 that during rotation of the loop the current and E. M. F. varied. This variation in magnitude is represented in Fig. 314, which is constructed similar to Fig. 313, but the current gradually rises to its maximum value of 5 amperes, P to A, and as gradually diminishes again to zero, A to B, during the first second, which may also represent one half revolution of the loop. Corresponding with the second half revolution, the current gradually rises from B, reaching its maximum negative value at C (three-quarter revolution), and falls again to zero at D, and so on.

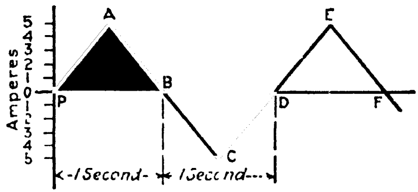


Fig. 314. — Graphical Representation of an Alternating Current.
Wave shape is triangular

In an alternating-current generator the alternating current wave is not so abrupt as that depicted in Fig. 314, but more truly represented by the undulatory curve, Fig. 315, which represents the same general variations as before. Thus at the end of one half second the current reaches its maximum value, 5 amperes, represented to scale by the line AG, while the value of the current at one quarter second is equal to the line KL, or about 3.5 amperes.

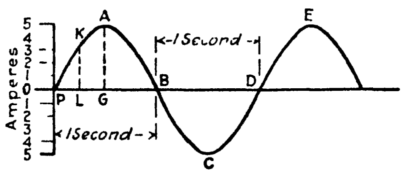


Fig. 315. — Graphical Representation of an Alternating Current.
Wave shape is sinusoidal

279. Magneto Alternator. — The E. M. F. produced by a generator depends upon:

(a) *The number of lines of force cut by the armature wires,*
(b) *The number and length of the cutting wires,*
(c) *The speed at which the armature revolves.*

The E. M. F. of the single-loop armature of Fig. 311 will

therefore be increased by winding it upon an iron core called the *armature core*, as in Fig. 316, which greatly increases the number of lines of force between the poles N and S, and also by winding a great many turns in the same direction around this core. Fig. 316 illustrates a Siemens *shuttle armature*, which is revolved between the poles of the permanent magnets NS; it is called a *magneto generator*, because the field is produced by permanent magnets.

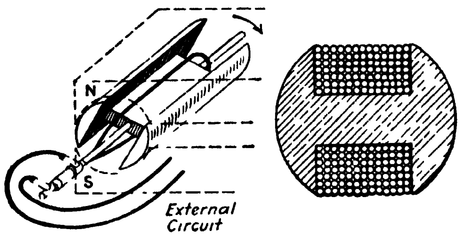


Fig. 316. — Siemens Shuttle Armature.

Only one turn is illustrated, but the shuttle is filled with wire, as in the cross-sectional view. This construction is only employed in small machines, such as those used with magneto telephone systems (Fig. 317), for gas engine ignition systems, and for testing insulation of lines. For generating large currents, generators are employed in which strong fields are produced by electromagnets and in which the armature core is laminated to prevent excessive loss of energy by eddy currents.

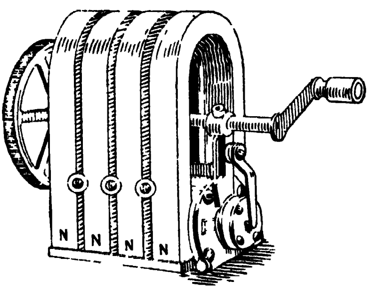


Fig. 317. — Magneto Generator for Telephone Ringing.

280. Simple Direct-Current Generator. — When it is desired to have the current from a generator flow always in one direction in the external circuit, like a battery current, for such purposes as charging accumulators, electroplating, etc., a *commutator* must be substituted for the collector rings in the simple alternator of Fig. 311. The function of a commutator is to *reverse* or *commute* the alternating current of a generator at the proper instant in each revolution before it flows through

the external circuit. It is practically a split ring, mounted upon a hub *insulated* from the *shaft*, with the parts of the ring also *insulated from each other*. Brushes rest upon the split ring at diametrically opposite points. The scheme of a simple bipolar direct-current dynamo is illustrated in Figs. 318 and 319, from which the act of commutation can be studied. In Fig. 318 the wire AB is rotated down past the S-pole. The direction of current is from B to A, by the right-hand rule, and to the external circuit by brush M, which is *positive*; then

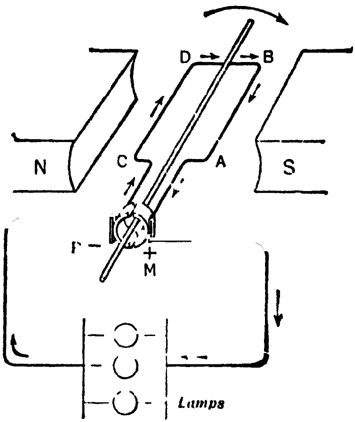


Fig. 318. — Simple Direct-current Generator.

At the instant depicted in the revolution brush M is positive

from the lamps to the negative brush P and around the loop, CDBA. When the loop is rotated one half revolution (Fig. 319), AB will move up past the N-pole and the direction of current in it will be *reversed*. Its terminal, however, is not *now* in contact with *brush* M, *as before, but connected to brush* P. Current flows to the external circuit from the brush M, which is *still positive*, though the current in the armature has been reversed, as in an alternator. Brush M is conse-

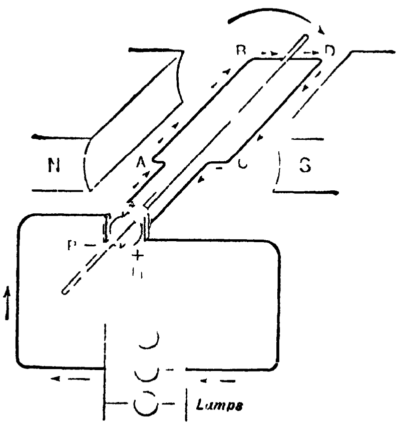


Fig. 319. — Simple Direct-current Generator.

Direction of current in the coil at one-half revolution from the position in Fig. 318; brush M is positive as before

quently *always positive* and brush P always negative, or the current in the *external circuit* is a *direct current* flowing in one direction only.

The act of commutation occurs at the instant when the wire, moving down past the **S**-pole, commences to move up past the **N**-pole, each terminal of the coil being connected with one brush for one half revolution and with the other brush for the other half of the revolution. With a two-part commutator, the current in the external circuit is interrupted twice in each revolution. A single coil armature of several turns is shown in Fig. 320, wherein it is seen that the direction of the current is the same for all the wires on the same side of the coil. In what direction is the coil supposed to be revolving in this figure?

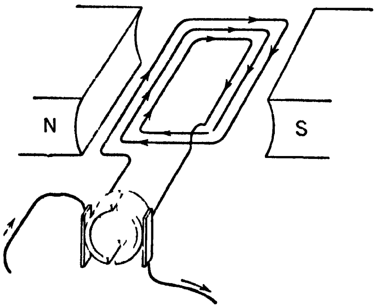


Fig. 320. — The Induced E.M.F. of each Turn is in Series with that of every other Turn.

Experiment 95. – Make the same connections for the student's experimental dynamo as given in Experiment 94. Adjust the brushes so that they bear lightly upon diametrically opposite points of the *two-part commutator*.

(a) Upon revolving the shaft slowly the needle is now deflected to one side of the zero mark.

(b) Reverse the direction of rotation, and the direction of deflection (or polarity of the brushes) is also reversed.

(c) Increase the speed and the deflection increases. Why?

(d) Increase the field strength by grouping the magnet coils in parallel, leaving the poles **N** and **S** as before; the deflection will be found greater than before for the same speed of rotation. Why?

Experiment 96. — (a) Repeat Experiment 84, page **349**, to determine the direction that the galvanometer needle deflects for a given direction of current.

(b) Test with a compass the field poles of the student's experimental dynamo of Fig. 312 and mark the polarity of the pole pieces.

(c) Determine, with the aid of the galvanometer, the positive **brush for a particular direction of rotation.**

(d) Apply the right-hand rule, ¶ 259, and note whether the polarity determined by this method agrees with that already determined.

(e) Reverse the polarity of the fields and again prove this rule.

281. Graphic Representation of a Direct Current. — The same method is applicable for illustrating the direction and magnitude of a direct current as given in ¶ 278 for an alternating current. Since there is no reversal of current in the external circuit, the curve will lie above the time line (Fig. 321), and represents the magnitude of E. M. F. or current at each instant during the rotation of the loop in the bipolar field. The curve indicates a pulsating current of 5 amperes maximum value flowing always in one direction.

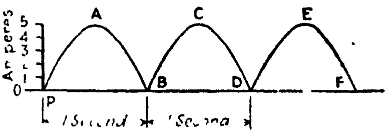


Fig. 321. — Graphic Representation of a Direct-current from a Single Coil.

282. Multi-Coil Armatures. — With an armature composed of a single coil of wire the current in the external circuit is very pulsating as the coil passes through the various phases of induction represented by the curve in Fig. 321. In Fig. 308, consider two coils to be placed at right angles to each other; then, at the instant shown, the current in the vertical coil will be zero, while that in the horizontal coil will be a maximum. As rotation is continued the current in the one coil, ABCD, increases as that in the other, abcd, decreases until, at quarter revolution, current in coil A is maximum and in coil a, zero, and so on. There will thus always be current flowing in one of the two coils, so that if they are properly joined to an external circuit the current will be less pulsating than when a single coil is used. This is depicted in the current curves of Fig. 322, where the curve ABCDE represents the current wave from one coil and curve FGHIJ shows that from the other coil, and where the heavy line AKGLCMINE represents the pulsating character of the current produced by

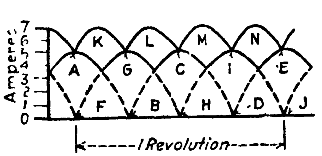


Fig. 322. — Representation of a Direct-current from a Multi-coil Armature.

the two coils acting together in the same circuit. The current is thus never zero in the line as in the curve of Fig. 321, but varies from a minimum value of 5 amperes to a maximum of about 7 amperes. The armatures of dynamos are wound with many coils of wire, so that the current may be continuous in the external circuit. These coils are angularly disposed on the iron core of the armature.

283. — Principle of the Motor. -- The principles involved in the rotation of the armature conductors, when carrying a direct current and located in a magnetic field, were fully discussed under the subject of Electrodynamics, Lesson XV. It was also shown in ¶¶ 214 and 224 how a single loop, placed in a magnetic field, could be made to rotate, by commutating the current through it at the proper instant in its revolution, and how the turning effort was increased by increasing the number of loops or coils and arranging them at different angles with reference to the field. When the loops are distributed around an iron core, and then placed in a powerful magnetic field and a current passed through them, each loop tends to move to the position in which it encloses the greatest number of the lines of the field. The direction in which each loop will move will be such that its lines of force will be in the same direction as the lines of force of the field; the force with which it will move, or the turning effort or torque (¶ 315) will depend upon the strength of current flowing through it (that is, the strength of current driving the motor), the size of the loop, and the density of the lines of force through it. When the loop arrives at the position where it accommodates the greatest number of the lines of force through it in the same direction as its own lines, the force, or turning effort, stops. If moved past this position the electrodynamic force is reversed and now tends to turn the coil back to the position of maximum lines of force through it. To obtain continuous rotation, the current through each loop must be reversed at the instant that the turning effort ceases. These reversals are automatically performed by the commutator, when the brushes are correctly set and adjusted.

In a generator the direction of current in the armature is such as to oppose the motion producing it, Lenz's Law; the

reaction increases as the current from it increases, thereby requiring additional power to drive it as the load increases. The reaction of the current in the armature of a generator is thus opposed to the direction of rotation of the armature.

In a motor, the reaction of the magnetic field of the armature conductors upon the magnetic field surrounding them is such as to move the armature wires across the field in the same direction as the armature rotates, and it is this force which is used to perform mechanical work at the motor pulley. The greater the load applied to the pulley of a motor the greater will be this force or turning effort (torque), and consequently the greater the current taken by the motor armature from the supply mains (¶ 314).

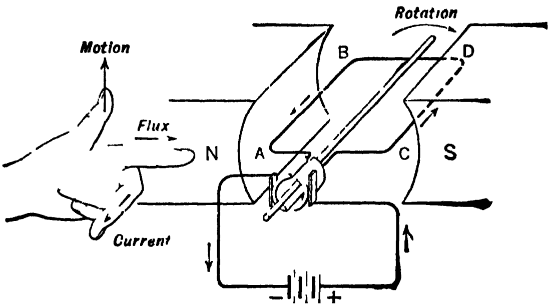


Fig. 323. — Single Loop Armature Driven as a Motor.

284. Direction of Rotation of Motors. — The direction of rotation of a motor, or that in which any dynamo will rotate when used as a motor, can be found by the left-hand rule (¶ 189) when the polarity of the field magnets and the direction of current through the armature have been ascertained. Place the left hand, as shown in Fig. 323, so that the fingers correspond with the polarity and direction of current in the single armature coil motor, and it is found that the loop will rotate in the direction of the hands of a clock. The direction of rotation of a motor can be changed by reversing the current either through the armature or through the fields, but not through both. If both are changed, the motor will run in the same direction as before. See ¶ 191.

Experiment 97. — Separately excite the field magnets of the student's experimental dynamo, Fig. 312; adjust the brushes so as to make contact with the *collector rings;* place the armature coil with its plane horizontal and pass a current through the armature. The coil is urged around until its plane becomes vertical, when rotation ceases, according to the principle outlined in ¶ 283. Incline the coil at any angle to the vertical position, and upon closing the circuit it rotates to the vertical position and stops.

Experiment 98. — Now adjust the brushes upon the *two-part commutator* and repeat Experiment 97. The coil rotates continuously in one direction, the direction of current being reversed by the commutator at each half revolution.

Experiment 99. — Find the polarity of the field magnets with a compass, also the polarity of the supply line, and note whether the direction of rotation is according to the left-hand rule.

QUESTIONS

1. How does a generator differ from a primary battery as a source of electricity?
2. Classify dynamos according to their mechanical construction.
3. How does an alternator differ from a direct-current generator?
4. Why are large generators constructed with multipolar rather than bipolar fields?
5. Sketch four positions of a single rectangular coil of wire at each quarter of a revolution in a bipolar field. Assuming the terminals of the coil to be provided with two collector rings, indicate polarities and direction of the current in the internal and external circuits in each sketch.
6. Make sketches when the terminals of the coil in Question 5 are connected to a two-part commutator.
7. The armature of a generator revolving at 1000 revolutions per minute generates 110 volts. State two ways in which you can increase the voltage, using the same armature.
8. State the operating principle of the direct-current motor.

LESSON XXIV

ARMATURES

Gramme Ring Armature — Induced E. M. F. in a Ring Armature — Drum Armature — Open-Coil Armatures — Eddy-Current Loss — The Commutator and Brushes — Armature Core Insulation — Table XX — Armature Windings — Hysteresis Loss — Armature Reactions — The Act of Commutation of an Armature Coil — Improvements in Commutation — Causes of Sparking — Questions.

285. — Gramme Ring Armature. — A four-coil direct-current *Gramme* ring armature is illustrated in Fig. 324. The ring is made of a number of laminated sheets of soft iron and the coils wound upon it. The ending of each coil is joined to the beginning of the adjacent coil, so that the winding forms a complete closed circuit, or the coils are all in series. At the junction of each coil with its neighbor a lead wire is run to a commutator section, so that instead of the two-part commutator of ¶ 280 one with four sections is now used. As the number of coils is increased the commutator sections are increased, as will be noted in subsequent figures. An eight-coil ring armature is depicted in Fig. 325, rotating with the hands of a clock in a bipolar field. The connections are the same as those given above. The magnetic lines of force issuing from the **N**-pole flow through the upper and lower halves of the core to the **S**-pole; very few lines cross the air space inside the ring. The direction of current in the coils on the two vertical halves of the ring is indicated by arrows and is found by the right-hand rule, ¶ 259.

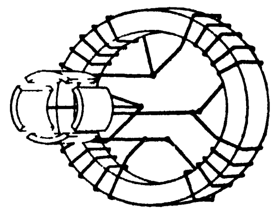


Fig. 324. — Four-coil Gramme-ring Direct-current Armature.

When the external circuit is closed the induced current flows in both halves of the winding toward the upper or positive brush, and returns from the external circuit to the lower

or negative brush, circulating up again through each half of the armature. The windings in the halves of the armature are in parallel with the brushes. As each coil passes from under the influence of the **N**-pole and comes into action under the **S**-pole, commutation takes place and the direction of current through it is reversed, as will be seen by tracing the direction of the currents in the two upper coils, which carry currents opposed to each other. The brush is located at this point of opposition and serves to conduct the current from both halves of the ring to the external circuit. The brushes resting upon two adjacent bars will thus short-circuit each coil for an instant as it passes from pole to pole, and this short-circuiting should occur when there is little E.M.F. in the coil. The circulation of current through the windings of a ring armature rotating in a four-pole field is shown in Fig. 326. The direction of rotation is counter clockwise, and the direction of current through the windings under any particular pole can be found by the right-hand rule. The currents in the windings under the upper **N**- and **S**-poles are opposed to each other and flow to the external circuit by the + brush 1 and back

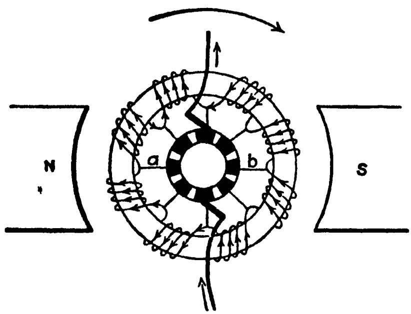


Fig. 325. — Eight-coil Gramme-ring Direct-current Generator Armature.

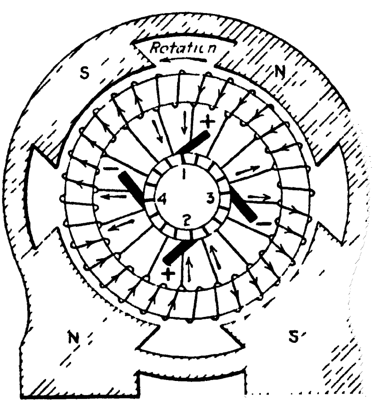


Fig. 326. — Direction of Current through the Windings of a Multipolar Ring Armature of a Generator.

to this half of the armature by − brushes 3 and 4. At the same instant the opposed currents in the lower windings flow to the external circuit by + brush 2 and return to the armature through − brushes 3 and 4. The armature is thus divided into four circuits and four brushes are required and must be placed between the poles so as to short-circuit the coils as they pass through the neutral space. In this form of winding there is no difference of potential between the + brushes, so that they are connected in parallel, as are also the negative brushes, and then to the external circuit. In multipolar machines there are as many brushes as pole pieces,[1] and all the + brushes are generally connected to one main generator cable, forming the + terminal of the machine, and likewise with the negative brushes.

286. Induced E. M. F. in a Ring Armature. — The upper and lower coils in the right-hand half of the ring armature (Fig. 325) will have about the same E. M. F. induced in them, say 20 volts each, while the two coils between them will have a higher E. M. F. at the same instant, say 40 volts each, since they occupy nearly the position of the maximum rate of change of the lines threading through them. The total E. M. F. of this half of the ring, since these *four coils* are in *series*, will therefore be 20 + 40 + 40 + 20 or 120 volts, and since similar induction takes place in the other half of the ring at the same instant, there will be a total of 120 volts induced in it. The windings of the *two halves being in parallel*, the E. M. F. at the brushes will also be 120 volts, just as though each half represented a battery of 120 volts E. M. F. and the two batteries were placed in parallel. The current in the external circuit will be the sum of the currents in each half of the winding. If it is 10 amperes, 5 amperes will flow through each half of the ring. The addition of the E. M. F.'s in the coils, and the current flowing from them, may be understood from the following battery analogy. In Fig. 327, eight batteries represent

[1] Since opposite commutator bars are of the same potential on this four-pole dynamo they may be joined by a cross-connecting wire and two brushes, as 2, and 4, dispensed with. This can only be done when there is an even number of coils. The armature is said to be "cross-connected."

the above armature coils and are connected 4 in series and 2 groups in parallel. The E. M. F. of one group of batteries is the sum of the E. M. F.'s of the batteries connected in series in that group, or 20 + 40 + 40 + 20 = 120 volts, and the E. M. F. of 2 groups in parallel is 120 volts. If 10 amperes flow through the external circuit, 5 amperes will flow through each group of batteries.

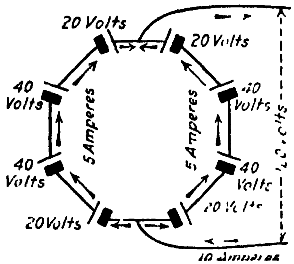


Fig. 327.—Battery Analogy of Induced E.M.F. in a Ring Armature.

By employing 8 coils on this ring armature the current is less pulsating than in the four-coil armature of Fig. 324. As the number of armature coils is further increased, the wave becomes more nearly a straight line, but there will always be a slight pulsation of the current.

Problem 118.—The joint resistance of the two halves of an 8-pole ring armature is 0.5 ohm. This is called the *armature resistance* and would be measured between the brushes. What is the resistance of all the wire upon the armature?

By Formula (32) R = J. R. × nq.
Here J. R. = 0.5 ohm, nq = 2 halves in parallel, and therefore
R = 0.5 × 2 = 1 ohm.

This is the resistance of one-half the armature, therefore the total resistance of the wire upon it = 1 × 2 = 2 ohms. The total resistance of the armature winding is thus four times the joint resistance from brush to brush in this type of armature.

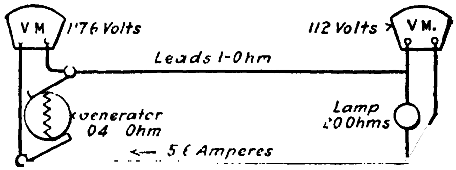


Fig. 328.—E.M.F. and P.D. of an Armature.

The resistance of an armature should be considered in determining the current that will flow in a circuit connected with the generator. The voltage available at the brushes of the machine will be less than the generated voltage by the voltage necessary to send the current through the armature resistance, ¶ 301.

Problem 119. — The E. M. F. generated by the ring armature in Fig. 325 is 120 volts, the resistance of the armature is 0.4 ohm, of an incandescent lamp connected to the brushes 20 ohms, and of the leads to the lamp 1 ohm. What current will the lamp receive? See Fig 328. What potential will a voltmeter indicate when placed across the brushes?

If R and r be respectively the external and internal resistance, then by

Formula (35) $I = \frac{E}{R + r} = \frac{120}{20 + 1 + 0.4}$ 5.6 amperes.

Formula (28) $E = I \times R = 5.6 \times (20 + 1) = 117.6$ volts.

The pressure required to send 5.6 amperes through the armature will be $E = I \times r = 5.6 \times 0.4 = 2.4$ volts, or $120 - 117.6 = 2.4$ volts.

By substituting a pair of collector rings for the commutator, the ring armature of Fig. 325 will give an *alternating current* to the external circuit. The winding is the same, but only two lead wires are taken from the coils, at points diametrically opposite and connected one to each collector ring. With the increased number of coils the alternating E. M. F. is increased, since the E. M. F.'s in the coils at any instant are in unison. The commutator and collector rings may both be mounted on the same armature shaft, in which case the machine will give either a direct or alternating current, or both, at the same time to two independent circuits. The dynamo would then be called a *double-current generator*. The collector rings would be connected to diametrically opposite sections of the commutator; for example, a and b in Fig. 325.

287. Drum Armature. In the ring armatures already considered the wire forming the coils is wound in and out around the core, as shown in Figs. 324 to 326. Only that part of the wire which is located on the periphery of the ring cuts the magnetic lines of force and is therefore active in developing E. M. F. That part of the wire is termed the *active wire*, while that on the ends and inside of the ring, which serves only to connect one active conductor to the next, is called the *dead wire*.

In the *drum armature* both sides of each coil are made effective in producing E. M. F. by placing them on the periphery, usually in slots in a cylindrical laminated iron core. In consequence drum armatures have a greater percentage of active wire and a lower I^2R loss than a ring armature of the same

dimensions. The two coil sides are so located that when one side is under a N-pole the other will be under the next adjacent S-pole. *In a bipolar field this means that the coil sides are* about diametrically opposite, as shown in Fig. 329, while in a four-pole machine each armature coil subtends one-quarter of the surface between its two sides, etc. The electromotive forces induced in the two sides of a coil will then be cumulative, that is the two E. M. F.'s will be in series. In practice a great many coils are placed on the core, covering its entire surface, the number of commutator segments increasing with the sub-division of the armature winding.

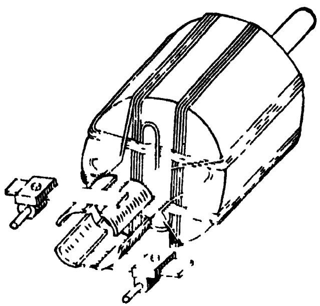


Fig 329. Four-coil Drum Armature.

Both halves of the drum armature coils are in parallel so that the induced E. M. F. of the machine is that generated by one-half of the total conductors upon the core, and each half of the windings deliver one-half of the total current flowing to the external circuit. Drum armatures are used almost to the exclusion of the ring type.

There is no necessity in drum armatures for employing solid cylindrical cores except in armatures of small diameter. In larger armatures the laminated core need only extend inward back of the winding slots to an extent allowing sufficient iron cross section for the magnetic lines of force. Such cores are assembled on a mechanical support, called a *spider*, which is later mounted on the shaft (Fig. 330). This construction affords splendid cooling facilities, and is economical in iron. While its general form is that of a ring, drum armature cores of such construction should not be confused with the practically little-used ring armature.

Fig. 330 depicts a drum armature of an Allis-Chalmers generator, having its core built up from punchings of thin sheet steel and held in position by two rings securely fastened to the spider arms. The coils are first wound, then properly shaped upon formers, removed, wrapped with insulation,

varnished and baked to expel all moisture, and then placed in the slots of the armature core. The winding is held in place by retaining wedges and the end connections are held by banding wire. The coil terminals are properly connected to the commutator. In some types of large size generators, solid copper bars, properly insulated, varnished, baked, etc., are placed in the armature slots, which are lined with mica formed

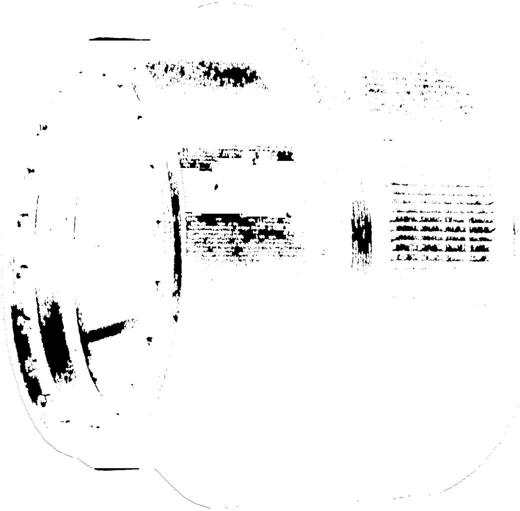


Fig. 330 — Armature and Commutator Mounted on Spider or Quill

tubes. The bars are then connected by flexible formed terminals, according to the method of winding.

288. Open-Coil Armatures. — The armatures previously described are called *closed-coil armatures*, because the coils are all connected to form a closed winding around the armature. Generators for series constant-current, street-lighting circuits, which were formerly used to a large extent, were generally equipped with open-coil armatures. A simple ring armature of this type is depicted in Fig. 331. Two coils, A and B, wound at opposite positions on the ring core, are connected

in series to two diametrically opposite commutator bars, 1 and 2. Another pair of coils, C and D, is wound in a position at right angles to the former coils, and the two coils are connected in series to two independent diametrically opposite bars, 3 and 4. At a particular instant during the revolution, shown in Fig. 331, the coils C and D have the maximum E. M. F. induced in them, and are connected to the external circuit by the brushes. while coils A and B are in the position of zero induction and out of circuit at this instant. An instant later coils A and B will be in the active position and connected to the circuit while coils C and D are cut out. Two independent two-part commutators are used instead of that shown and placed side by side, one set overlapping the other. By making the brush equal to the width of both sets of bars, the external circuit is not broken each time a pair of coils is switched out of circuit. With the four-coil armature the current would be very pulsating in the external circuit, so that more coils are used with correspondingly more commutator segments, or several commutators placed side by side on a shaft, and their respective brushes connected in series or parallel with the external circuit.

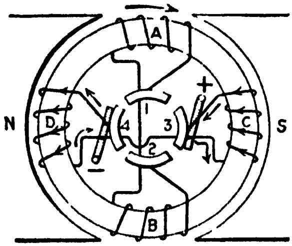


Fig. 331 — Open-coil Armature.

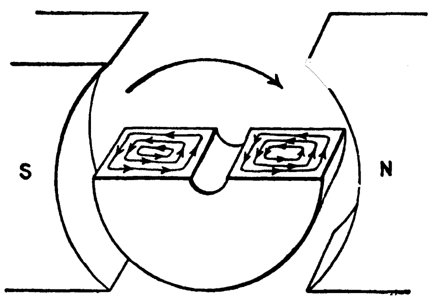


Fig. 332. — Eddy Currents in the Armature Core.

289. Eddy Current Loss.— The armature core which is introduced into the magnetic circuit of a dynamo to lower its reluctance is an electrical conductor also, and when rotated in the magnetic field will have currents induced in it, according to

the principles of electromagnetic induction. A certain portion of the energy driving the armature is thus expended in producing useless electric currents, *eddy currents* (¶ 263), in the core and which do not appear in the external circuit; this is termed *eddy current loss*, and constitutes one of the internal losses of a dynamo. A section of a solid armature core is illustrated in Fig. 332, and the direction of the induced eddy currents, as determined by the right-hand rule (¶ 259), is indicated. The flow of these currents represents a waste of energy appearing as heat in the core. The armature wires being wound on the core will also be heated and their resistance increased, and as a result the I^2R loss will be raised.

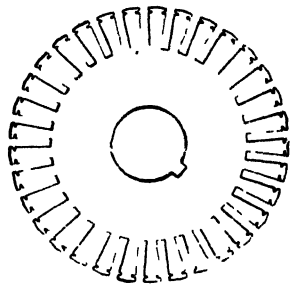


Fig. 333. — Sheet Iron Armature Lamination

Eddy current losses may be considerably diminished by building up the armature of a series of thin disks of soft sheet iron or steel, the surfaces of which have been allowed to oxidize (rust), thus introducing an insulator between the sheets, which decreases the electrical conductivity of the core. Sometimes pieces of tissue paper or coats of insulating varnish are interposed between the sheets to break the continuity of the electric circuit. A single sheet iron punching of a tooth-core armature is represented in Fig. 333, while the effect of lamination is shown in Fig. 334, in which the eddy currents are confined to each lamination. By laminating armature cores in this way the resistance of the entire path of

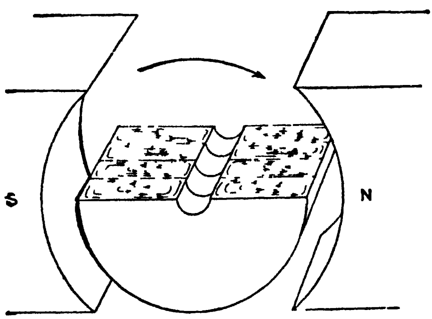


Fig. 334. — Laminated Armature Core.
The thickness of disks is magnified to show the eddy currents

eddy currents is greatly increased and therefore the strength of these currents diminished. The eddy current loss in the 4-disk core of Fig. 334 is only $\frac{1}{16}$ of that in the solid core of Fig. 332 for otherwise identical conditions. To reduce this loss still further a great many disks are used for a single armature core; indeed, the thickness of the metal from which laminations are punched may be as small as 0.014 inch.

290. The Commutator and Brushes. — A commutator consists of a number of bars or *segments* of drop-forged or hard-

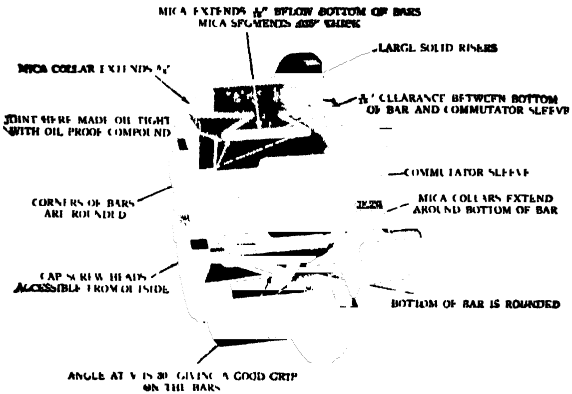


Fig. 335. — Sectional View of Commutator.
Made by Reliance Electric & Engineering Co.

drawn copper, assembled around an iron hub and thoroughly insulated from the hub and from each other (Fig. 335). Mica is used for the insulation, its thickness usually varying from 0.02 to 0.15 inch, depending upon the voltage of the machine. The bars must be securely held in place, since a high or low bar would cause a break in the circuit each time it passed under the brush and destructive arcing would result.

In the construction of a commutator, the segments and mica strips are assembled and clamped firmly together by an external temporary steel ring. Grooves are then turned into the inner surface to fit the commutator sleeve and the clamping ring, as illustrated in Fig. 335, and thereafter the various

parts are securely clamped together by cap screws. The external steel ring is now removed and the outside surface of the commutator is machined into a true cylinder. The manner of locking the commutator bars without short-circuiting them

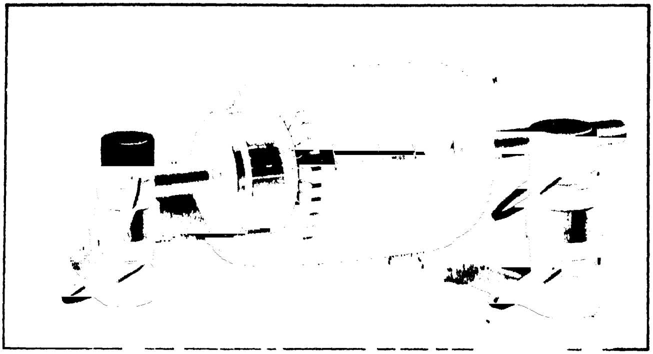


Fig. 336. — Armature for "Peerless" Motor.
At each end is shown a bearing with its oil rings

will be understood from an inspection of Fig. 335. A lug or *riser* extends at right angles from one end of each bar to which the armature lead is soldered. Fig. 336 shows the completed armature.

The current is conducted to and from the armature by means of brushes which are guided by brush holders and made to press against the commutator by spring pressure. Brush holders should be carefully designed so as to avoid vibration of the brushes, a common cause of sparking. Details of a brush holder are shown in Fig. 337. The brush holder stud or shaft is securely bolted to, but insulated from, the rocker arm or brush holder yoke, and connected by flexible cables to the external circuit. The function of the rocker arm is to move the position of the brushes upon the commutator so that the current is led to and from

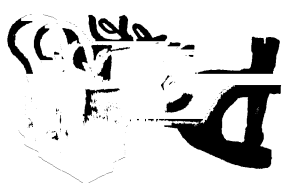


Fig. 337. — Brush Holder (General Electric Co.)
Brush slides freely in holder. Connection is made by stranded copper wire called a pigtail.

the armature at the proper points of commutation. Brushes are generally made of hard graphitic carbon, although in low-voltage dynamos brushes of copper gauze are used to advantage because of their lower resistance. Copper brushes are also used in some turbine-driven generators.

291. Armature Core Insulation. – The armature cores of generators are slotted for the reception of the conductors, which must be thoroughly insulated from the core. Windings may be insulated with micanite, pressboard, paper, cotton, varnished cloth, etc., the amount and quality depending upon the potential to be developed by the armature.

The quality of an insulating material is tested by subjecting it to a high potential and ascertaining at what voltage the insulation "breaks down," or conducts, instead of insulates. The specimen to be tested, as a piece of paper or fiber, may be interposed between two plates connected to a source of high potential, which is capable of being regulated. The voltage is then increased till a spark passes from plate to plate through the specimen, thereby puncturing it. The following table shows some insulating materials and the voltages at which they "broke down" under test:

Table XXI. Insulation Test

Material	Thickness in inches	"Break down" voltage
dry cotton tape	0.013	250
soft gray wrapping paper	0.010	1,000
asbestos paper	0.015	1,500
varnished cloth	0.010	7,500
red sheet fiber	0.037	7,000
press board or fuller board	0.022	5,000
micanite	0.018	11,000

The insulation of electrical machinery is usually tested by applying a greater voltage than the apparatus is designed to stand; for example, a 1000-volt armature may be subjected to 3000 volts, one terminal of the high potential source being connected to the core, and the other to the copper windings.

The standard test voltage for many classes of apparatus is twice the normal voltage of the circuit to which the apparatus is connected, plus 1000 volts. If there is any defect in the insulation, upon application of the high voltage it will readily be noted on indicating instruments in the testing circuit.

In large machines the conductors are generally in the form of straight bars of rectangular cross section which have been previously insulated. One or more bars are inserted in each

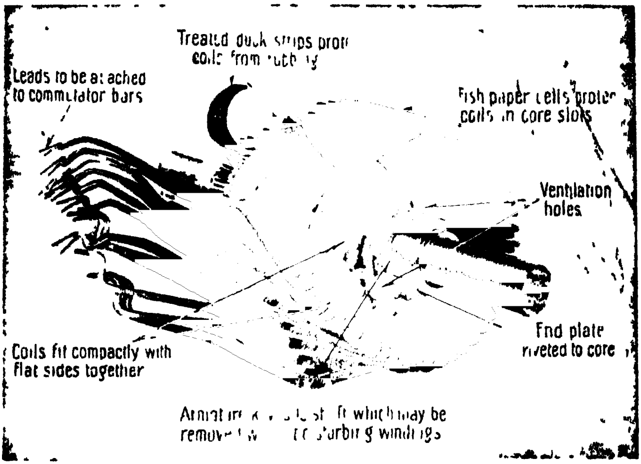


Fig. 338. — Partly-wound Armature Showing Method of Assembling Coils

slot, and the coils formed by connecting their ends to other bars by flexible formed end terminals soldered to them, provision being made for commutator taps at the ends of the proper coils, when the armature is for a direct-current machine.

It is not advisable to use bars of very large cross section because of the eddy currents set up in them when one side of a conductor happens momentarily to be in a stronger field than the other. Instead it is best to use several smaller conductors of equivalent total cross section and connected in parallel at the commutator.

In medium sized multipolar machines the windings consist of a number of formed coils, each coil being composed of several conductors of round or rectangular wire individually insulated and then fastened together with cotton, linen or varnished cloth tape. Such formed coils possess superior insulation and permit of speedy removal in case of repair without disturbing adjacent coils. Fig. 338 illustrates the method of assembling the formed coils of an armature of a type SK Westinghouse motor.

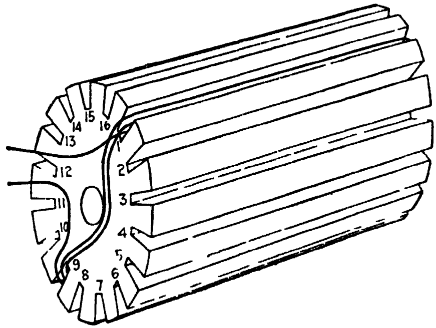


Fig. 339. — Position of a Coil on a Bipolar Drum Armature.

292. Armature Windings. — The coils of an armature may be connected to each other and to the commutator segments in a variety of ways that will yield satisfactory operation. Practical armature windings are economical in copper, render satisfactory commutation, and are accessible for making repairs. Present windings are designated as single or multiplex windings, two-circuit (wave) or multiple-circuit (lap) windings, etc.[1]

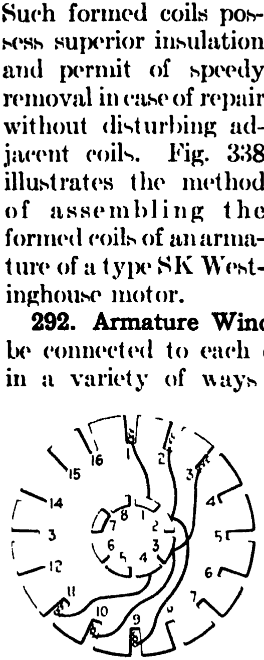


Fig. 340. — Connecting the Armature Coils to the Commutator.

A small drum armature for a bipolar field is shown in Figs. 339 and 340. Suppose it is to be wound as a closed-coil armature with 8 coils and 3 turns per coil. The armature core would have 16 slots and the first coil wound in slots 1 and 9; the second in 2 and 10, and so on. Commence to wind the beginning of coil No. 1 in slot 1; and its third turn will end in slot 9, Fig. 340; commence coil No. 2 in slot 2, wind in the same direction as the first and it will end in slot 10,

[1] Armature winding is treated in books relating to dynamo design.

and so on. The coils should then be bound to the armature core by mounting it in a lathe and winding several bands around it, each consisting of a number of turns of phosphor bronze wire, soldered together. A commutator with 8 bars will be required since there are 8 coils and the coils are to be joined in series. Connect the beginning of coil No. 1 to bar 1 and the ending of coil No. 1 to bar 2, Fig. 340; the beginning of coil No. 2 to the ending of coil No. 1 at bar 2; the ending of coil No 2 to bar 3 and to the beginning of coil No. 3, and so on until finally the

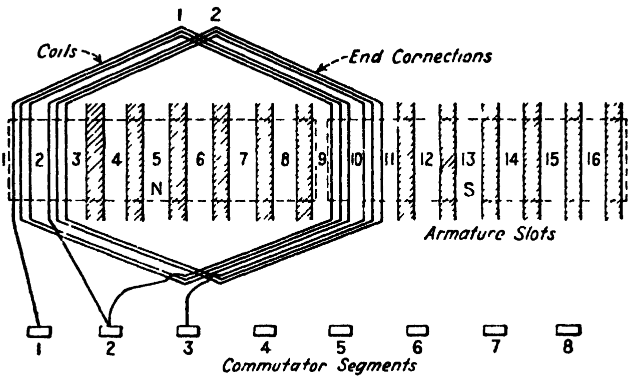


Fig. 341. — Developed Bipolar Armature Winding.

ending of coil No. 8 will connect to the beginning of coil No. 1 at bar 1. The coils are thus all in series around the armature, the commutator bars forming the connecting links between the coils. Fig. 341 shows the same winding *developed,* that is, the armature and commutator surfaces are rolled out flat; such diagrams are often used.

The two types of armature windings now in use are illustrated in Fig. 342, the names *lap* and *wave* being derived from the arrangement of the coils which are traversed successively by the current. The coils of the lap winding are divided into as many groups as there are poles and these groups are joined in parallel; whence the name *multiple-circuit winding.* The coils of the wave winding are joined in series in one or the other of two groups and these groups are joined in parallel; whence the name *two-circuit*

winding Lap-wound dynamos must have as many brushes as the machine has poles, while wave-wound machines may have only two. The lap winding permits of a wide choice in the number of coils and slots, the wave winding is better adapted for high voltage.

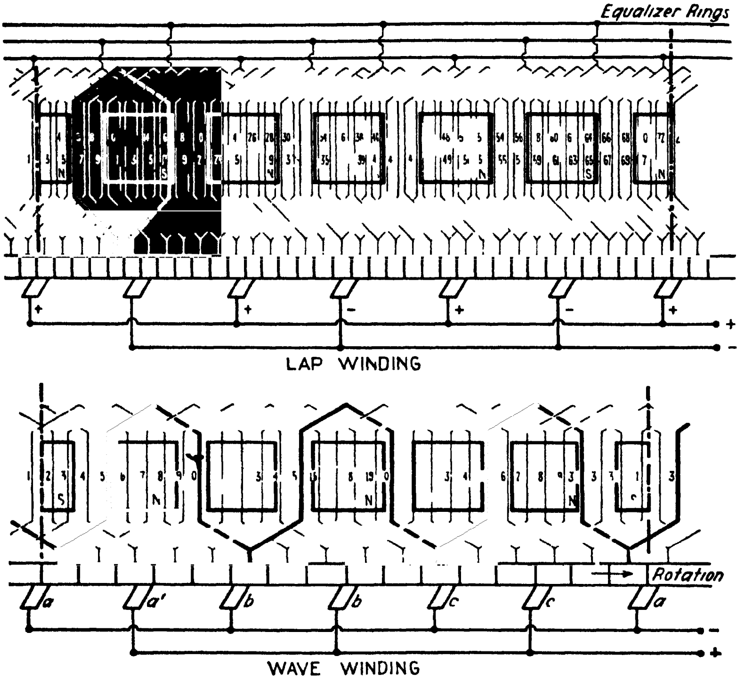


Fig. 342. Multipolar Armature Windings.
Both windings are for 6-pole dynamos. Brushes b, b, c and c may be omitted in the wave winding.

There may be many turns of wire per coil in order to increase the induced E. M. F. After the first set of coils is wound a second set may be wound on top of them with proper insulation in the slots between them. 16 commutator bars would have been required had this method been adopted in Fig. 341. There would then be two coil sides a and b in each slot as shown at B in Fig. 343. The method of varying the winding

according to the potential desired is illustrated in Fig. 343, which represents the number of wires per slot on a 5-kw. dynamo when it is wound for 125 volts, as in A; 250 volts, in B; 500 volts, in C. The size of the wires decreases as the voltage increases, since for the same power the current will be less, and the turns increase in direct proportion to the voltage, there being 3, 6 and 12 turns per coil to correspond with 125, 250 and 500 volts. The speed and field strength are assumed the same for each armature.

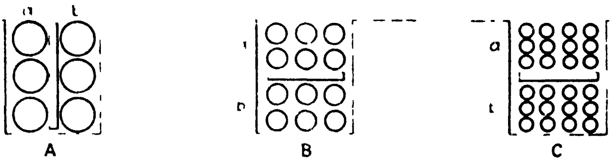


Fig. 343. — Windings of a 5-kw. Armature.
A — 125 volts B — 250 volts C — 500 volts

The following illustration will give the student some details of a direct-current generator armature.

Rating: 400 kw., 240 volts, 10 poles, 200 rev. per min.

Core: 58 in. diameter, 12 in. long, 200 slots 1.6 in. deep and 0.43 in. wide.

Winding: 1-turn multiple winding having 4 conductors per slot, section of conductor 0.55 × 0.14 in.

Commutator: 32 in. diameter, 13 in. long, 400 segments.

293. Hysteresis Loss. — The iron core of a drum armature rotating in a two-pole field will be subjected to two opposite magnetic inductions in each revolution. For example, consider the polarity of the core at one instant during its revolution (Fig. 344); the left-hand side of the core has a **S**-pole induced in it by the **N**-pole of the field magnet, while the right-hand side of the core possesses an induced **N**-pole from the **S**-pole of the field magnet at the same instant. After one half revolution of the core from this point that part which previously possessed induced **N**-polarity is now inductively magnetized with a **S**-pole and the other half with a **N**-pole. The core is thus subjected to two opposite magnetizations in each revolution. Suppose the speed to be 2000 revolutions per minute,

then there will be 4000 reversals of magnetization per minute in the core. This reversal involves molecular friction, called hysteresis, and causes the development of heat (¶ 264, Experiment 88). A portion of the energy required to drive the armature is thus expended in heating the core and does not appear as useful electrical work. The heat so generated also heats the copper wires wound upon the armature core, increasing their resistance and the I^2R loss, so that still more energy is wasted which does not appear as useful energy. This hysteresis loss, together with the eddy-current loss (¶ 289), constitutes the *core loss* in a dynamo.

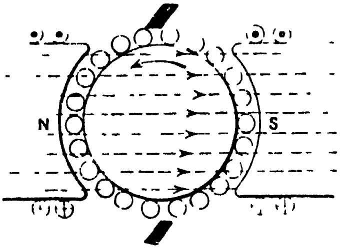


Fig. 344. — Armature Core Loss due to Hysteresis

294. Armature Reactions. The current flowing from a generator armature circulates through its internal windings and produces magnetic poles in the armature core which react upon the magnetic field, which produced the armature current. If a current be sent from some outside source through this armature with its own field magnets unenergized, it would set up a magnetic field, as illustrated in Fig. 345. The conductors are here shown on the surface of the armature with the current flowing toward the observer in the left-hand conductors and away from him in the right-hand conductors. It is seen that the axis of the field N-S is across that of the main field, as shown in Fig. 344 and is therefore termed *cross flux.*

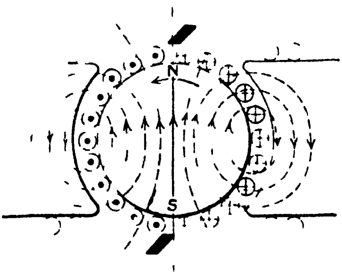


Fig. 345. Magnetic Field Produced by Current Circulating through the Armature

In the operation of this armature as a generator both the main field and cross field exist at the same time, and the entire

field is obtained by combining Figs. 344 and 345, with the result shown in Fig. 346.

In the upper half of the right pole piece the direction of the cross flux (Fig. 345) is the same as that of the main field (Fig. 344) consequently the resultant flux there is intense; whereas in the lower half of that field pole the two fluxes are opposed and the result is a weak field. These conditions are represented in Fig. 346 by the closeness of the lines of force. The distribution of these lines through the generator field poles and armature is therefore non-uniform, or the main field is said to be distorted by the armature flux.

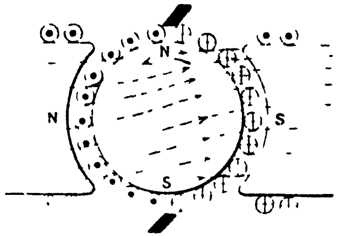


Fig. 346. Distortion of the Magnetic Field due to the Cross-magnetizing Effect of the Armature Current.

The position of maximum induction then is not along the horizontal line, as considered in the ideal dynamo (¶ 276) but along a line inclined at an angle to it, the angle increasing as the current from the armature increases. As a result of this field distortion the position of minimum inductive action in the armature coils will not be along the vertical line marked neutral plane in Fig. 347, but along a line somewhat in advance of it, in the direction of the armature rotation, as the line ab, which is perpendicular to the resultant flux axis of Fig. 346. Commutation of an armature coil should therefore take place as the coil passes the line ab, which is therefore called the *commutating plane*. The brushes should be set at diametrically opposite points (in a bipolar dynamo) and then shifted to a

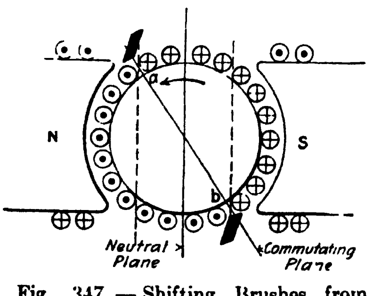


Fig. 347. — Shifting Brushes from Neutral Plane because of Armature Reaction.

position corresponding to the commutating line. The angle of advance of this line from the vertical position will depend upon the current flowing from the armature (the field distortion increasing with the current), being shifted forward for an increase, and backward for a decrease in the armature current. The brushes must therefore be shifted forward in the direction of rotation for an increase of current from the machine, and backward for a decrease. When the brushes are not set to correspond with the commutating plane, sparking at the brushes may result.

295. The Act of Commutation of an Armature Coil *Sparking at the Brushes.* The act of commutation of an armature coil, that is, its passage from under the influence of one pole to go under that of the other, is illustrated in Fig. 348. For an instant, each coil is completely short-circuited by the brush, and during that time the current that was flowing in it must be reduced to zero and brought up again to full value in the opposite direction. While at the point A (Fig. 348), a definite amount of magnetic flux encircles the coil because of the current in it. This flux should consequently disappear and be reestablished in the reverse direction before the coil is transferred to the other side of the brush at C. It was pointed out in ¶ 266 that when the flux surrounding a coil due to its own current is varied, an electromotive force is induced which is called an E. M. F. of self-induction. Likewise, in the armature coil undergoing commutation, the changing flux develops an E. M. F. of self-induction, which in this case is commonly called *reactance voltage*. The presence of this voltage in the short-circuited coil is undesirable, for suppose its value at a particular moment to be 1 volt, then the current circulating through that

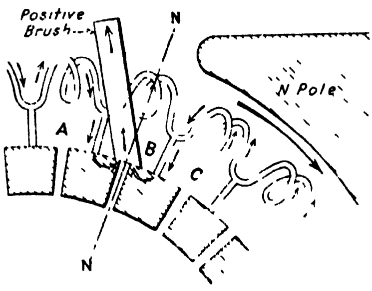


Fig. 348. – The Act of Commutation of an Armature Coil.

At the instant shown coil B is short circuited by the brush.

coil and the toe of the brush which together, may have a resistance of say 0.01 ohm, would be $I = \frac{E}{R} = \frac{1}{0.01} = 100$ amperes.

This current flow through a short-circuited coil may be reduced by the introduction of (1) resistance in the coil circuit, or (2) an opposing E. M. F. into the coil at the time of commutation. Resistance increase is usually affected by the use of carbon brushes rather than of high-resistance leads from armature winding to commutator, and an opposing E. M. F. may be obtained by so placing the brushes that the coil will cut a small amount of flux from that field magnet pole toward which the coil is moving. That is, the plane of commutation is shifted so that the coil, while short-circuited at a brush, will pass through a magnetic field of opposite direction of such strength that an E. M. F. will be induced in the coil sufficient to reverse the direction of the initial current in spite of the reactance voltage, which is developed by the varying flux due to the changing current in the coil. If the current strength in the coil after reversal is identical with its original intensity, then the coil may be transferred to the other side of the brush without disturbance, and sparkless commutation will be achieved. In practice, to find the *non-sparking brush-position of a generator* when it is running, *the brushes are rocked backward or forward until the sparking practically disappears, or until a point is found where it becomes a minimum.*

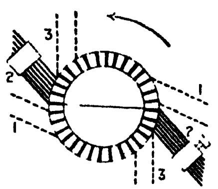


Fig. 349. — Shifting the Position of the Brushes. 1 — Full load 2 — Half load. 3 - No load

The tendency of a dynamo to spark can be greatly reduced if, in construction, the armature is divided up into many coils. Each coil will then have relatively few turns, and its inductance and therefore its reactance voltage will be small (the inductance of a coil is proportional to the square of the number of its turns, Formula 100). The reactance voltage of modern dynamos seldom exceeds 3 volts per segment, and splendid commutation is obtained.

Many dynamos, however, do spark at the brushes, but the

fault lies in the manner of adjusting the brushes, etc., rather than in the design of the machine. Some of the causes of sparking are given in ¶ 297.

The greater the current output of a machine the greater must be the E. M. F. induced in the short-circuited coil to effect the reversal of its current. This means that with increasing load the coil undergoing commutation must be brought into a more intense field. This is accomplished in older machines by shifting the brushes. In Fig. 349 is shown somewhat ex-

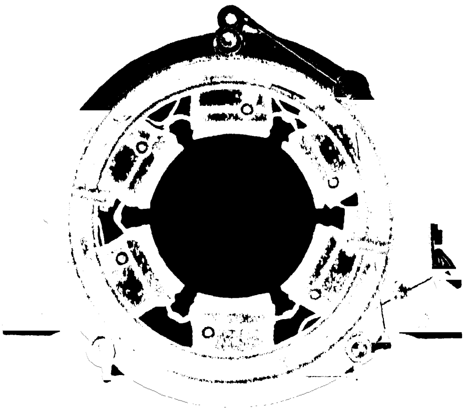


Fig. 350. — Field Frame of a 150-kw. Generator.

Illustrates brush shifting mechanism.

aggerated the relative positions of the brushes of a 2-pole generator running at: 1st, full load; 2d, half load; 3d, no load. The brushes are therefore gradually advanced from position 3 to position 1 as the machine is loaded, and likewise rocked backward from 1 to 3 as the load is diminished. The shafts which hold the brushes are attached to a cradle or arm, which can be moved to properly shift the brushes. Fig. 350 shows the shifting device used in an engine-type generator.

296. Improvements in Commutation. — It will be remembered from ¶ 294 that the current in the armature of a dynamo is responsible for the cross flux which produced distortion of the magnetic field and necessitated a shift of the brush axis.

If the magnetomotive force which sets up this cross flux were always neutralized by an equal amount oppositely directed, then there would be no transverse flux, and shifting of the brushes would be unnecessary when the load on the machine

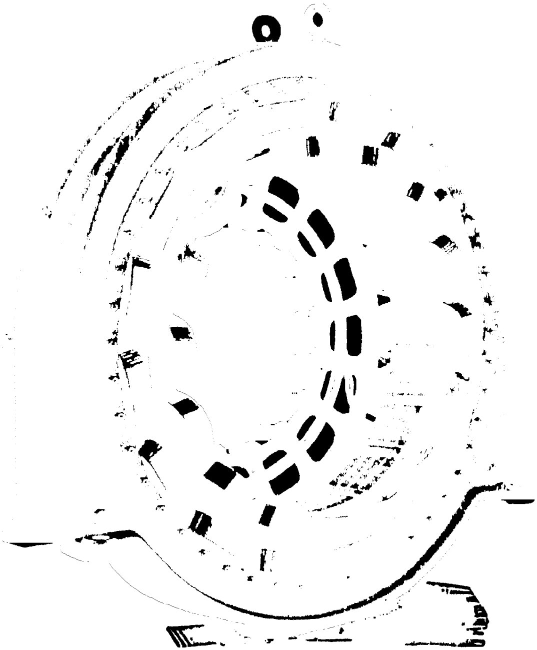


Fig. 351. — Field Frame of a Generator Showing Compensating Winding.

Outer coils constitute the main field winding, inner coils comprise the compensating winding

changes. This compensating magnetomotive force should preferably be provided in such a manner that the armature coils undergoing commutation would have E. M. F.'s induced in them which would balance the reactance voltage (¶ 295) at all loads and reverse the direction of current in these coils. Then the brushes might be permanently and centrally located

for all loads and for either direction of rotation, with satisfactory commutation.

The compensating magnetomotive force above mentioned may be provided by a winding embedded in slots in the field poles through which the armature current is passed. This construction is illustrated in Fig. 351, which shows the field frame of a 250-kw., 16-pole generator made by the Ridgway Dynamo and Engine Co. The field poles and yoke are entirely of laminated steel, and the compensating winding occupies slots in the pole faces.



Fig 352. — Field Frame of Interpole Motor.

Shows relative position of main (large) and commutating poles

The use of auxiliary poles between the main field poles of dynamos is effective in reducing armature reaction by producing a magnetomotive force approximately balancing that of the armature. These poles are called *inter-poles* or *commutating poles*, and provide in the region between the main poles a field of such strength and direction as will set up the proper E. M. F. in the coils undergoing commutation for the reversal of current. The coils on the interpoles are traversed by the entire armature current, or by a definite part of it. The field structure of a dynamo with commutating poles, manufactured by the Electro Dynamic Co., is shown in Fig. 352. Interpoles are especially used on shunt motors for variable speed service and in series motors for railways.

The General Electric Co. in its Type RF adustable speed motors utilizes both the compensating winding and interpoles. Fig. 353 shows the field frame of a 4-pole motor of this type with and without the coils assembled. Successful commu

tation of high peak loads at any speed within a range of 100% to 400% of its minimum speed in either direction is claimed for this motor.

297. Causes of Sparking. — In properly designed and constructed dynamos, sparking may ensue because:

1. Brushes are not set at the commutating plane. They should be rocked until this position is found. Brushes should



Fig. 353. — Frame of Compensated Interpole Motor

Showing construction of main and interpoles

Showing compensating coils embedded in main poles and the other coils in place

be accurately and equally spaced on the commutator so that they have the same number of commutator bars between them.

2. Brushes are set with insufficient pressure against the commutator.

3. Brushes are not set to obtain the full area of contact with the commutator.

4. Brushes vibrate or chatter.

5. A high, low, or loose commutator bar causes poor contact with the brush.

6. Loose connection exists between armature coil and commutator bar. This will be noted by a peculiar blue snappy spark just as this particular bar passes under the brush.

7. Commutator is worn in ridges, causing an uneven surface for brush contact.

8. Armature section is either short-circuited by a breakdown in the insulation or open-circuited in the winding. If the machine can be stopped for a short time this coil should be disconnected, its ends taped, and a wire of the same size as that used in the armature used as a bridge to connect the commutator bars formerly connected to the detached coil. The continuity of the armature circuit will thus be maintained and the machine can be run until the coil can be rewound.

9. Overload on the dynamo. This will be noted by the ammeter in the circuit, also by the sparking of the brushes and the increased temperature rise of the machine.

10. Collection of dirt and grease on the commutator, which assists in preventing a good brush contact. Carbon or copper particles may short-circuit some commutator segments. The commutator must be kept clean.

QUESTIONS

1. What is the difference (a) between a drum and a ring armature? (b) between a closed-coil and an open-coil armature?

2. Make a sketch of a 12-coil direct-current bipolar ring armature with two turns per coil; indicate the direction of current in the armature coils and in the external circuit.

3. The resistance of all the wire wound upon a bipolar armature is 2 ohms. What is the armature resistance? *Ans.* 0.5 ohm.

4. The armature in Question 3 generates an E. M. F. of 50 volts. What current will flow through some lamps joined in parallel with it if the lamps have a joint resistance of 4 ohms; resistance of lead wires is 1 ohm? *Ans.* 9.1 amperes.

5. What will be the P. D. indicated by a voltmeter, in Question 4, when placed (1) across the lamps? (2) across the brushes? *Ans.* (1) 36.4 volts; (2) 45.5 volts.

6. What is meant by laminating an armature core? Why is this necessary?

7. State three ways in which energy is uselessly expended in the armature of a dynamo.

8. What is the neutral plane and the commutating plane of a dynamo?

9. Locate the proper positions of the brushes in a bipolar generator when the armature rotates against the hands of a clock.

10. Why should a coil be commutated as it passes through the commutating plane?

11. Since a two-part commutator is so simple in construction, why are armature windings subdivided into many coils, thus necessitating many commutator bars?

12. In some generators it is necessary to change the position of brushes for changes in the current flowing from the machine. Why is this?

13. What is the total output current of the 400-kw. armature described in ¶ 292? How much current does each conductor carry? *Ans.* 1670 amps.; 167 amps.

14. A piece of mica subjected to an insulation test is said to have broken down at 1500 volts. What is meant by this?

15. An armature contains a defective coil. How would you temporarily remedy the trouble so that the machine could be operated?

16. What is the function of interpoles or compensating windings in a generator field?

17. State some causes for sparking at the brushes of a dynamo.

LESSON XXV

DIRECT-CURRENT GENERATORS

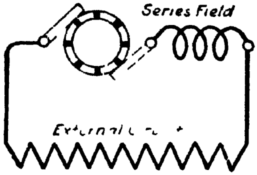
Classification of Dynamos according to their Field Excitation — The Self-exciting Principle of Direct-Current Generators — Residual Volts — The Shunt Generator — Action of the Shunt Generator — Action of the Series Generator — Compound Machines — Compound-wound Generators in Parallel — Three-Wire Generators — Capacity of a Generator — Commercial Rating of Generators — Losses in a Dynamo — Efficiency of a Generator — Questions and Problems.

298. Classification of Dynamos according to their Field Excitation. – The current for magnetizing the field magnets of a generator may be supplied from a separate generator or by the machine itself, it would be styled respectively a *separately-excited* or a *self-exciting* generator. The methods of *excitation* are, of course, independent of the field construction and depend only upon the windings and their connections. *Generators* may be classified according to the methods used to excite the field magnets as follows:

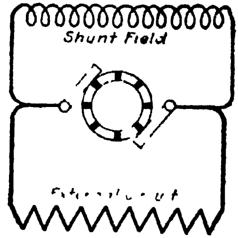
(a) *Magneto Machines* (Fig. 317). — The field magnets are permanent magnets of horseshoe form and the armature is designed for either direct or alternating current. Such machines supply limited power and are used chiefly in gasoline engine ignition work, telephone signaling, and testing of circuits.

1. Direct-Current Machines. —

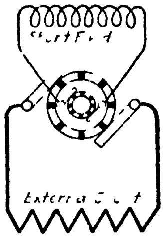
(b) *Series Machines* (Fig. 354) (*Constant Current*). — The field magnets are connected in series with the armature and wound with a few turns of heavy wire having a low resistance, so as to present little opposition to the main current flowing through them. Series generators are only used for series street-lighting circuits (¶ 288) and in the Thury system of high-voltage direct-current power transmission.



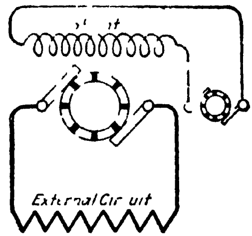
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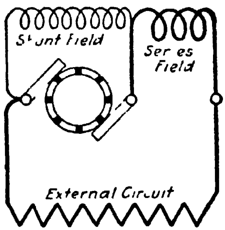
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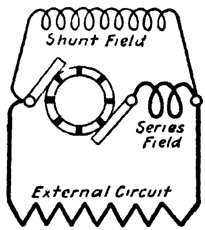
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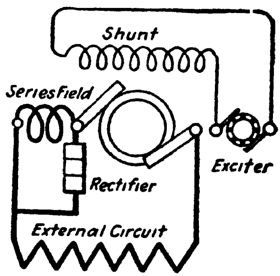
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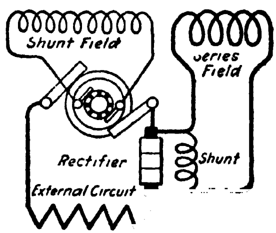
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359.



360.



361.

Figs. 354–361. — Classification of Generators according to the Method

In a *constant-current* circuit supplied by a series generator the current is maintained constant through the external circuit, while the E. M. F. varies with each change in the resistance of the circuit. Street arc or incandescent lamps, when operated in series from constant-current machines, usually carry 6.6, 7.5 or 9.6 amperes and the voltage may vary from 45 to 8000 volts, according to the number of lamps in circuit. The reason for operating these lamps in series is that they are generally distributed over a very large area, and an economy in copper is effected by employing a small wire, generally about No. 6, for the series circuit and using a high voltage. The direct constant-current system of street lighting is now little used.

(c) *Shunt Machines* (Fig. 355) (*Constant Potential*). — The field magnets are connected in parallel or shunt with the armature and are wound with many turns of small wire; they have a high resistance, compared with the armature, since only a small portion of the main current need flow through them.

(d) *Separately-Excited Machines* (Figs. 356 and 357) (*Constant Potential*). – Current for the field magnets is supplied from a separate generator. In Fig. 356 this generator forms a part of the main machine by having a separate armature on the same shaft, while in Fig. 357 the field is supplied by a distinct machine called an *exciter*.

(e) *Compound Short-shunt Machines* (Fig. 358) (*Constant Potential*). – The field cores contain two independent spools. One is wound with a few turns of heavy wire, forming the *series coil*, and connected in series with the main circuit; the other, with a great many turns of smaller wire, forming the *shunt coil*, and connected in shunt with the armature.

(f) *Compound Long-shunt Machines* (Fig. 359) (*Constant Potential*). — The same as (e) except that the shunt field bridges not only the armature but also the series field; hence it is called a *long shunt*.

2. Alternating-Current Machines. —

(g) *Separately-excited Machines* (Figs. 356 and 357). — The field magnets are excited from an auxiliary generator (or exciter). Alternators require an exciter, since the alternating

current cannot be employed to excite the fields. The exciter may be either a separate generator or an independent direct-current winding upon the alternator shaft, thus rendering the machine self-contained. Fig 362 illustrates a 50-kw. engine-driven alternator, with its exciter direct-connected to the shaft.

(h) *Compound Separately-excited Machines* (Fig. 360). Two independent field windings correspond to the series and shunt coils of Fig. 358. The shunt coil is supplied from an

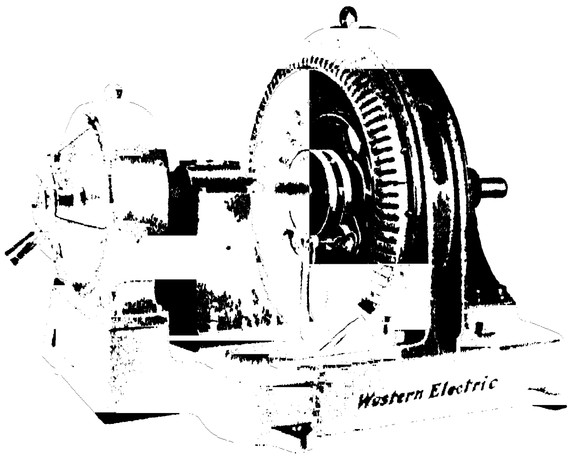


Fig 362. - Alternator with Direct-connected Exciter.

exciter while the main current, commuted, flows through the series field coils This method is employed in *composite-wound* alternators, a portion of the main alternating current is commuted by a special device called a *rectifier*, located on the armature shaft. Its function is to change that portion of the alternating current intended for the series coils into a direct current for producing the magnetization. A self-contained composite-wound alternator is depicted in Fig. 361.

The field circuit of all dynamos except those of small size should not be broken suddenly, because the voltage of self-induction may rise to such value as to injure the insulation (see Experiment 90). A discharge resistance and special field

switch are generally used, the magnetic energy of the field being converted into heat in the resistance.

299. The Self-exciting Principle of Direct-Current Generators — Residual Volts. — If the soft iron or steel field cores of a generator have once been magnetized they retain permanently a small amount of their magnetism. An armature revolving in even so weak a field as that due to residual magnetism will cut some lines of force, and as a result there is an E. M. F. maintained at the brushes without any excitation. This is often spoken of as the *residual volts*, and will be indicated upon a voltmeter connected to the brushes, when the field circuit is open, and the armature revolves at its proper speed. This E. M. F. may be from 2 to 10 volts or more, depending upon the quality of the iron, the number of armature conductors, etc. If now the field circuit be properly connected to the brushes, a current will flow through the field magnets due to the residual volts; the number of lines of force of the field increases with this increase in field strength; the induced volts also increase and cause additional current to flow around the fields, resulting in a further increase of voltage at the brushes. This action continues until the maximum voltage of the machine is attained. The process has been termed "the building up of the field," and may be observed by the increasing deflection of a voltmeter, or by the gradual increase in the brilliancy of a lamp, called a *pilot lamp*, connected to the brushes when any direct-current shunt-wound dynamo starts to generate. Ten to twenty seconds may be required from the time the field switch is closed until the armature generates its full voltage. A machine may refuse to build up, owing to the loss of its residual magnetism, in which case the cores should be remagnetized.

Problem 120. — The resistance of the armature of a dynamo is 0.15 ohm and that of the field magnets, 100 ohms. With open fields the armature generates 6 volts, due to the residual magnetism. What current will flow around the field to start the building-up process when the field circuit is closed?

By Formula (35) $I = \frac{E}{R + r} = \frac{6}{100 + 0.15} = 0.059$ ampere.

300. The Shunt Generator — *Constant Potential.* — In a shunt dynamo (Fig. 363) the field coils are of comparatively high resistance as compared with the armature; for example, the multipolar field of a 125-volt, 10-kw. dynamo has a resistance of about 40 ohms, and the armature resistance is only 0.1 ohm. The field ampere-turns of a shunt generator are the product of a very small current and a great many turns, so that little of the electric energy generated will be used for their excitation. The regulation of the voltage in the external circuit of a shunt machine is accomplished by varying the current through the field coils, by means of a resistance inserted in series with them, and called the *field rheostat* (Fig. 363). Decreasing the resistance in the field rheostat increases the current around the field coils thereby increasing the ampere-turns, the number of lines of force cut by the armature, and the induced voltage in the armature winding. Inserting resistance in the field rheostat lowers the voltage available at the brushes.

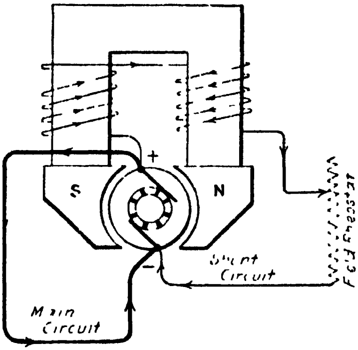


Fig. 363. — Shunt Generator.

The field magnets are connected across the brushes. A field rheostat regulates the voltage

The current flowing through the shunt field is equal to the potential difference at the brushes, divided by the resistance of the field plus that in the field rheostat (Formula 27).

The current flowing through the armature of a shunt generator is the sum of the currents in the field circuit and in the external circuit. The volts drop in the armature is equal to its resistance multiplied by the current flowing through it (Formula 28).

The resistance of the armature is usually measured by the voltmeter-ammeter method (¶ 228) and will be higher when the machine is carrying a load than when running idle on account of the resistance increase occasioned by heating. It is usually measured directly after a load test on the machine.

301. Action of the Shunt Generator. – In starting a shunt generator, after proper speed is attained, the machine is brought up to the required voltage by manipulating the field rheostat, and then the main switch connecting it with the external circuit is closed. Suppose that the voltmeter indicates 112 volts potential difference when the external circuit is open. The induced E. M. F. will be a little higher than this value and equal to $112 + I \times r$, where I equals the current through the fields and r equals the armature resistance. A voltmeter, therefore, placed across the brushes of any self-exciting generator indicates the potential difference rather than the induced E. M. F.

If the field rheostat is adjusted for any particular voltage with the main circuit open, say 112 volts, and the switch is now closed so that more current flows from the armature, the voltmeter at once indicates a lower voltage, say 108 volts. If the speed is the same as before, this loss is due to two causes: *first*, there is an increased drop in the armature due to the additional current flowing through it, which lowers the potential difference at the brushes; *second*, the potential difference at the brushes being lowered, less current flows around the field, so that there are not quite so many lines of force cut as before.

A statement of the voltages of a generator at no load and when carrying full load is spoken of as its *voltage regulation*. The *percentage regulation* is the ratio of the change in voltage between no load and full load to the voltage at full load.

To find the percentage regulation of a generator:

Obtain the difference between the no-load and full-load voltages of the machine and divide by the full-load voltage.

$$\%\ \text{voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{full-load voltage}} \quad \textbf{(101).}$$

Problem 121. – The voltage of a shunt generator when operating at no load is 112 and when operating at full load is 108. Find its voltage regulation.

By Formula (101) % regulation $= \frac{112 - 108}{108} = \frac{4}{108} = 0.037 = 3.7$ per cent.

The potential difference at the brushes thus varies in a shunt generator, with each change in load, *increasing as the load decreases and decreasing as the load increases.* If the current fluctuations are wide and quite frequent, an attendant would be constantly required to manipulate the field rheostat, or else some automatic device may be employed to keep the voltage constant. In consequence, shunt generators are adapted only to installations where the load is fairly constant,

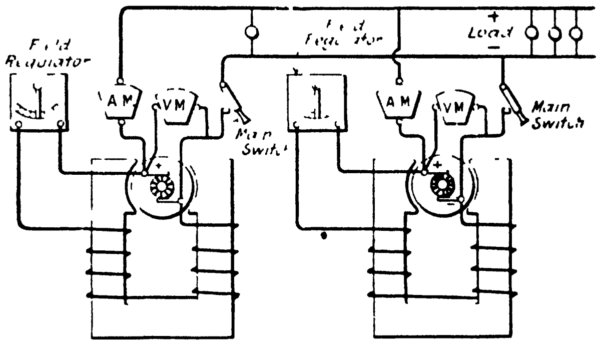


Fig. 364. Two Shunt Generators Connected in Parallel.

The voltage across the mains is equal to that of one machine, the current in the mains is equal to the sum of that of the two machines

when they will require very little attention after the proper adjustment of the field rheostat has been made.

Shunt generators may be connected in parallel when their voltages are equal by connecting the positive and negative brushes as in Fig. 364. The voltage is the same as with one machine, but the current output will be the sum of the currents each machine can furnish separately. The voltage of a machine, to be paralleled with other generators already in service, should be adjusted equal to, or a little higher than, their potential, after which adjustment it can be connected to the common circuit. Such machines in parallel operation are practically self-adjusting to load conditions. If one machine runs a little faster than the rest it will do more work, and vice versa. Their voltages should be carefully regulated so that the total load will be properly apportioned among them To

take load off one machine running in parallel with others, add resistance gradually in its field circuit, until the ammeter of that machine reads practically zero, after which its circuit breaker (Fig. 146) is tripped and the main switch opened.

Shunt generators will also operate in series, but if the machines are of different sizes, the current in the external circuit is limited to the capacity of the smaller machine. The polarity of the brushes of a shunt generator may be changed by either reversing the field connections to the brushes, or by reversing the direction in which the armature rotates. In the latter case the brushes will also have to be changed to agree with the direction of rotation.

Experiment 100. - The following test, No. 1, was made upon a certain 1-kw. shunt-wound generator and illustrates the falling of potential at the brushes as the load increases The voltmeter was placed across the brushes, the ammeter was placed in series with some lamps joined in parallel, and the shunt field rheostat was adjusted so that the E. M. F. was 110 volts with no load. The rheostat was *not adjusted* thereafter during the test. Readings of the voltmeter and ammeter follow for a constant speed of 1540 rev. per min.

Test No. 1.		Test No. 2.	
Amperes	Volts at Brushes	Speed	Volts at Brushes
1	108	2110	100
2	106	2200	104
3	103	2290	108
4	100	2380	112
5	97	2470	116

Experiment 101. — The field magnets of the foregoing generator were separately excited so that the lines of force cut were the same at all speeds. The field rheostat was adjusted so that the generator produced 100 volts at a speed of 2110 rev. per min. The voltage at various speeds is shown above for Test 2 and illustrates how the induced volts vary proportionally with the speed.

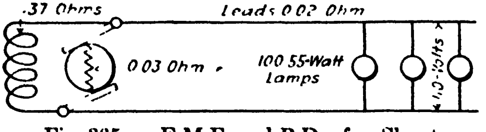


Fig. 365. — E.M.F. and P.D. of a Shunt Generator.

Problem 122. – A shunt generator, Fig. 365, maintains 110 volts across 100 incandescent lamps joined in parallel, requiring 55 watts and 110 volts each. The lamps are located some distance from the generator and the resistance of the leads is 0.02 ohm. Resistance of armature is 0.03 ohm and of field coils is 37 ohms. Find

(a) P. D. at brushes; (b) total E. M. F. generated, (c) watts lost in the armature, (d) loss in the field, (e) loss in the leads; (f) power supplied to the lamps.

By Formula (55) $I = \frac{P}{E} = \frac{55}{110} \times 100 = 50$ amperes for lamps.

(28) $E = I \times R = 50 \times 0.02 = 1$ volt drop in leads.

$110 + 1 = 111$ volts P. D. at brushes (a).

(27) $I = \frac{E}{R} = \frac{111}{37} = 3$ amperes through the fields.

$50 + 3 = 53$ amperes through the armature.

(28) $E = I \times R = 53 \times 0.03 = 1.59$ volts drop in armature.

$1.59 + 111 = 112.59$ volts total E. M. F. (b).

(54) $P = E \times I = 1.59 \times 53 = 84.3$ watts lost in armature (c).

$111 \times 3 = 333$ watts lost in fields (d).

$1 \times 50 = 50$ watts lost in leads (e).

$110 \times 50 = 5500$ watts supplied to lamps (f).

302. Action of the Series Generator (*Constant Current*). — In a series generator (Fig. 366) the field coils are in series with the armature, and have a low resistance, since the current from the armature flows through them to the external circuit. The field ampere-turns of a series generator, as compared with those of the shunt machine, are the product of a much larger current and a less number of turns. With the armature running at a constant speed, the E. M. F. and current from a series generator will vary with every change in the resistance of the external circuit, since each change of current alters the field magnetizing current, and consequently the E. M. F. induced in the armature. In practice the current from a series generator is required to be constant, irrespective of the resistance of the external circuit, while the

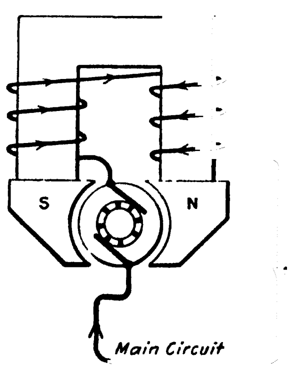


Fig. 366. — Series Generator.

voltage is altered to suit the conditions of the circuit. It is thus a *constant-current generator*. The regulation is accomplished by either of two general methods. In the first method the armature used is of the open coil type (¶ 288) and the position of the brushes is automatically moved so as to be in connection with the armature coils while they are passing through any stage of induction, from the points of maximum induced E. M. F. to the minimum. Any change in the current strength tending to change the field magnetism is thus neutralized by a corresponding opposite change in the E. M. F. The automatic regulator is usually a solenoid and core attached to the brushes and actuated by the main current. This method is utilized in the Thomson-Houston arc-light dynamo.

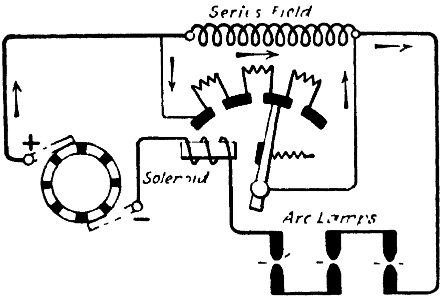


Fig. 367. — Regulating the Voltage of a Series Generator by Shunting the Series Field.

In the second method an adjustable rheostat is placed in shunt with the series field magnets (Fig. 367) and the main current divides in proportion to the resistances of the two circuits. The arm of the rheostat is automatically moved by a solenoid and core arrangement actuated by the main current. If the resistance of the external circuit is suddenly lowered, the increased current immediately actuates the solenoid and rheostat arm in a direction to decrease its resistance, thereby shunting more current from the field circuit, and preventing the rise of E. M. F. This second method is used in the Brush arc-light generator. Obviously a series generator will not self-excite when the external circuit is open, and will not "build up" when the external resistance is very high. This may be overcome by momentarily short-circuiting the machine while the external circuit is closed, when the E. M. F. will rise to a sufficient value to start the action. With a sensitive automatic regulator a series machine may be short-circuited without

injury, since the larger current which would tend to flow, immediately actuates the automatic mechanism in such a manner as to decrease the E. M. F.

Series generators were formerly used as constant-current generators for the operation of arc lamps connected in series, but few of them are now in service. The series field winding is still retained however in the compound-wound generator ¶ 303.

303. Compound Machines *(Constant Potential).* The compound-wound generator is designed to automatically give a better regulation of voltage on constant-potential circuits than is possible with a shunt machine, and possesses the characteristics of both the series and shunt dynamos. The shunt field is the same as in the shunt generator, and independent series field spools are added, through which the main current flows. These are connected so as to increase the magnetism of each pole produced by the shunt winding (Fig. 368). With no current in the external circuit the machine separately excites by its shunt field. When current flows to the external circuit the voltage at the brushes is not lowered, as in the shunt generator, since the series winding strengthens the field by the current flowing through it, and thus raises the voltage in proportion to the increased current. By a proper selection of the number of turns in the series coils, the voltage is thus kept automatically constant for wide fluctuations in load without changing the shunt field rheostat. If a greater number of turns is used in the series coil than required for constant terminal voltage at all loads, the voltage will rise as the load is increased, and thus make up for the loss on the transmission lines, so that a constant voltage will then be maintained at some point distant from the generator.

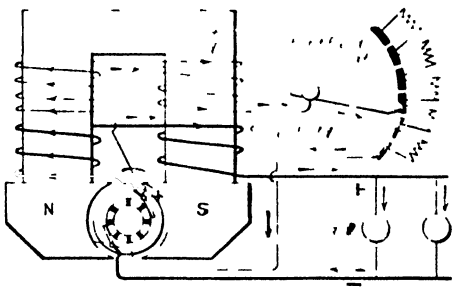


Fig. 368. Compound-wound Generator

The series and shunt fields act in unison

The machine is then said to be *over-compounded.* In lighting generators this over-compounding is usually designed for a rise of voltage from 3 to 5 per cent of that of the machine, from no load to full load. In design, the series field coils are wound with a slightly greater number of turns than actually required, and the amount of compound is determined by a load test after completion. These adjustments are made by placing a shunt around the series field so that the main current divides between the two circuits. The length of the shunt can then be regulated to send sufficient current around the series coils to produce the desired

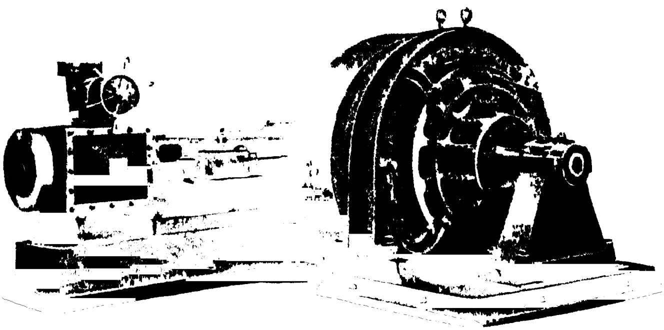


Fig. 369. — Ridgway Generator and Engine.

compounding. In a short-shunt compound-wound generator the shunt field is subjected to a higher voltage than with the long-shunt connections. The E. M. F. applied to the shunt field in the latter case for any particular load is equal to the E. M. F. at the brushes minus the drop on the series field (see Figs. 358 and 359). Compound-wound direct-current generators are extensively used in electric lighting and power stations and in electric railway power stations where the load is very fluctuating. A compound-wound generator direct connected to a steam engine is shown in Fig. 369.

A short-circuit on a compound-wound generator overloads the machine, since the excessive current flowing through the series field tends to keep the voltage at its normal value. Unless the line is automatically opened under such a condition,

ither by a fuse or automatic circuit breaker, the machine and ts driving engine will be damaged.

Experiment 102. – The following test was made on the 1-kw generator eferred to in Experiment 100. The series field was short-circuited in the revious tests, but both fields are acting in the present one The mahine was adjusted to 110 volts by the shunt field rheostat as before, nd *not changed* during the test. It will be noted that the potential as constant whether 1 ampere or 5 amperes were drawn from the machine. 'ompare with the shunt generator test in ¶ 301.

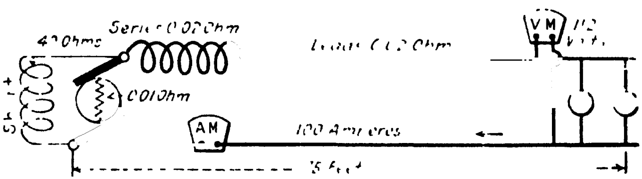


Fig. 370. — E.M.F. and Losses of a Compound-wound Generator.

Compound-wound Generator Test.

Amperes	Speed	Volts at Brushes
1	1540	110
2	1540	110
3	1540	110
4	1540	110
5	1540	110

Problem 123. A compound-wound generator (Fig. 370) supplies 100 mperes at 112 volts to a group of lamps located 75 feet from the genrator. Resistances are: leads 0.02 ohm; armature 0.01 ohm; series coil .02 ohm; shunt coil 40 ohms. Find

(a) P. D. at brushes; (b) total E. M. F. generated; (c) watts lost n the leads; (d) loss in the series coil; (e) loss in the shunt coil; (f) oss in the armature; (g) power supplied to the external circuit.

By Formula (28) $E = I \times R = 100 \times 0.02 = 2$ volts drop in leads.

$112 + 2 = 114$ volts P. D. at terminals.

(28) $E = I \times R = 100 \times 0.02 = 2$ volts drop on series field.

$114 + 2 = 116$ volts P. D. at brushes (a).

(27) $I = \frac{E}{R} = \frac{116}{40} = 2.9$ amperes through shunt field.

$100 + 2.9 = 102.9$ amperes, total current through armature.

(28) $E = I \times R = 102.9 \times 0.01 = 1.029$ volts drop in armature.

E. M. F. = 112 volts (lamps) + 2 volts (leads) + 2 volts (series coil) + 1.029 volts (armature) = 117.03 volts (b).

(60) $P = I^2 \times R = 100 \times 100 \times 0.02 = 200$ watts (c);

$100 \times 100 \times 0.02 = 200$ watts (d);

$= 2.9 \times 2.9 \times 40 = 336.4$ watts (e);

$102.9 \times 102.9 \times 0.01 = 105.88$ watts (f).

(54) $P = E \times I = 111 \times 100 = 11100$ watts supplied to external circuit (g).

304. Compound-wound Generators in Parallel. – Compound-wound generators are generally run in parallel, but more care must be exercised in connecting them in circuit than with shunt machines. In order to connect several compound-wound generators in parallel a special connection between the machines, called an *equalizing bar*, must be used. The function of this equalizer is to enable each machine to take its share of the load and to make the load on the machines so paralleled independent of slight changes in speed. The equalizing bar (Fig. 371) connects the brush of one generator, to which the series field is attached, to the corresponding brush of another generator. Both brushes, so connected, are of the same polarity and also of the same potential when the machines run at the same voltage.

The action is as follows: suppose the compound-wound generator No. 1 (Fig. 371) is carrying a load and it is desired to parallel machine No. 2 with it; the latter is brought up to speed and its voltage regulated by the shunt field rheostat F_2 until a voltmeter indicates that it is equal to that of No. 1. Though the terminals of the loaded and free machines now have the same potential difference, the voltage at the brushes of the loaded machine will be higher than that of the other, by an amount equal to the drop on the series field of No. 1. There is thus a difference of potential between the two ends of the equalizing bar, and when its switch E is closed, some current flows through the equalizer and around the series field of machine No. 2 to the external circuit. The line switch S_2 is now closed and the free machine takes some portion of the

load and is further regulated by its shunt field rheostat. When complete equalization of load occurs there will be no current in the equalizer. If the speed of either machine falls, thereby lowering its voltage, current from the other machine will flow through the equalizer and strengthen its series field, thus increasing the voltage. Sometimes no current will flow in an equalizer while at other times it may flow in either one direction or the other. To reduce the I^2R loss, the equalizer should be as short as possible and as large as the main generator cables.

A triple-pole switch is generally used for coupling a compound generator with others, the middle blade of which is

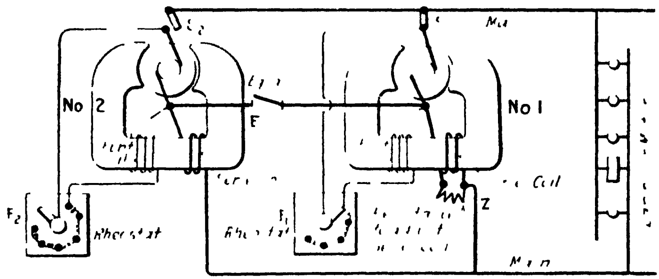


Fig. 371. — Two Compound-wound Generators Connected in Parallel.

slightly longer than the other two, and is connected to the equalizer. When the switch is closed the equalizer is connected first and the main terminals a little later. In shutting down a generator in parallel with others the main line terminals are first disconnected and then the equalizer is opened; this action is performed in one operation with the triple-pole switch alluded to above. The voltage should then be lowered by inserting all the resistance of the shunt field rheostat in circuit, after which this field circuit may be opened, and then the speed reduced.

Any number of compound-wound generators may be operated in parallel. If the machines are of different capacities they may also be run in parallel, provided that their voltages are the same, and that the resistances of the series fields are inversely proportional to the current capacities of the several

machines to be connected. Each machine will then take load in proportion to its capacity. The series fields can be adjusted by adding several turns of extra wire to this circuit, as required.

305. Three-Wire Generators. In the three-wire system of electrical distribution, which was described in ¶ 256, it is usual to have about 115 volts P. D. between each outside wire and the central or *neutral* wire, and twice that voltage between the two outside wires. Obviously two 115-volt generators might be connected in series and the neutral wire

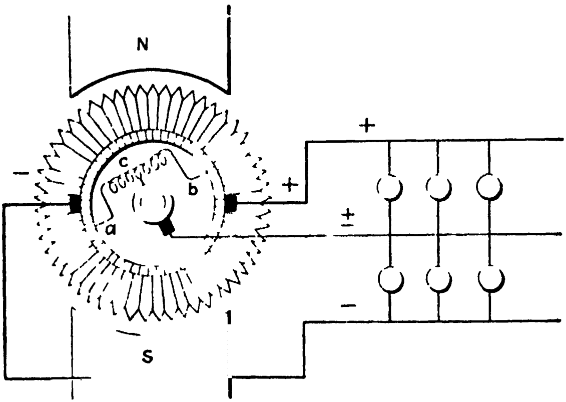


Fig. 372. — Three-wire Generator Having Reactance Coil Mounted on Armature.

joined to the connection between the machines (see Fig. 276), but this arrangement involves the expense for two machines. Therefore machines have been designed to meet this condition so that only one generator, called a *three-wire generator,* is necessary to supply a three-wire distribution circuit.

In one type of three-wire generator, originally designed by Dobrowolsky, a low-resistance coil of wire wound on an iron core is mounted on the armature and connected as shown in Fig. 372. In a bipolar machine this coil is connected to the regular armature winding at points a and b which are diametrically opposite, and the neutral wire is joined to the midpoint c of the coil by means of a slip ring and brush. The E. M. F. across the terminals a and b is alternating, and conse-

quently an alternating current will flow through the coil, but its value is small because of the large inductance of the coil. The midpoint c will then have a potential midway between the potentials of the brushes connected to the outside wires. If the load taken from one side of the circuit is the same as that from the other, no direct current will flow through the coil nor in the neutral wire. But if the loads are unbalanced the neutral wire and the coil will carry a direct current whose strength depends upon the amount of unbalance. Fig 373 shows the armature of a three-wire generator made by the Burke Electric Co. The coil in this machine is wound in the same slots with the armature winding.



Fig. 373 — Armature of Three-wire Generator
Midpoint of revolving coil connects with the slip ring

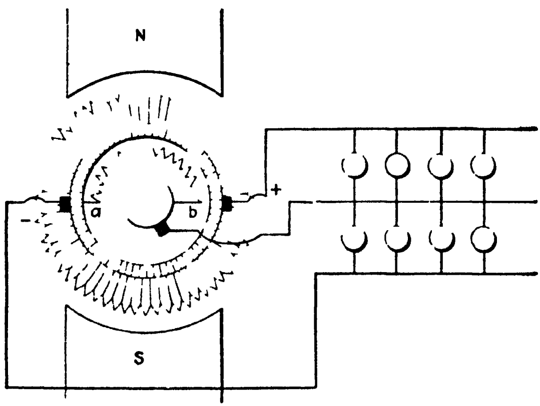


Fig 374 — Three-wire Generator with Auxiliary Winding.

Another type of three-wire generator produces the voltage for the neutral wire by a separate winding ab as depicted in

Fig. 374. This winding contains just half the number of turns between the slip ring and the point a, where it connects with the main winding, that there are in the latter winding between brushes, and in consequence the auxiliary winding will generate one-half the voltage that exists between the brushes. The Crocker-Wheeler Co. manufactures generators on this principle, but employs several auxiliary windings properly connected and distributed in the regular slots over the armature face.

In compounded three-wire generators the series field coils are divided into two equal sections, one section being connected in series with one of the outer wires and the other section in series with the other outer wire.

306. Capacity of a Generator. -- The capacity or rating of a generator depends very largely upon its heating when in service, and also upon commutating conditions. Eddy-current and hysteresis loss in the core, together with copper loss in the armature and field windings, produce heat in the generator, and its temperature continues to rise until the heat is dissipated as fast as it is produced. Since the copper loss increases very rapidly with load (heat increases four-fold when the current is doubled (¶ 237) a limit is soon reached beyond which the machine could not be run without speedy deterioration. This limit is imposed chiefly by the insulation employed. The American Institute of Electrical Engineers in its Standardization Rules gives the limits for *hottest-spot temperatures* of insulations as follows:

O. - Cotton, silk, paper and similar materials when neither impregnated nor immersed in oil 90° C. or 194° F.

A. Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, also enameled wire — 105° C. or 221° F.

B. Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only - 125° C. or 257° F.

If this maximum temperature be exceeded, the insulation may be endangered, and in addition the excess load may lead to injury by exceeding limits other than those of temperature, such as commutation, stalling load and mechanical strength.

In determining the temperature of different parts of a machine a thermometer is applied to the hottest accessible part of the completed machine and the hottest-spot temperature for the winding is obtained by adding a correction of 15° C. (27° F.) to the highest temperature observed, in order to allow for the practical impossibility of locating the thermometer at the hottest spot. When the thermometer is applied directly to the surfaces of bare windings, such as an edgewise-wound strip conductor or a cast copper winding a correction of 5° C. instead of 15° C. is made. For commutators, for collector rings, or for bare metallic surfaces not forming part of a winding, no correction is applied. Thermometers used for taking temperatures of machines should be covered by felt pads $1\frac{1}{2}$ inches × 2 inches × $\frac{1}{8}$ inch, cemented or puttied on. Measurements of temperature of windings may also be made by means of their increase in resistance or by the use of embedded temperature detectors such as thermal couples.

In order to determine the continuous rating of a machine it is operated under load conditions until a constant temperature difference between the machine and the surrounding air is reached. Under full load this may require from 6 to 20 hours, according to the size and construction of the machine.

In testing a generator for operation in locations where the ambient air temperature will not exceed 40° C. (104° F.), the permissible rise of temperature as observed by thermometer would be 221 − 27 − 104 = 90° F. for Class A insulating materials, and would be 221 − 104 = 117° F. for the commutator.

307. Commercial Rating of Generators. — Direct-current generators are rated in size, according to the number of kilowatts which they are capable of maintaining in the circuit external to their terminals within the limit of permissible heating. For example, a 50-kw., 100-volt generator means that the machine will deliver without excessive heating 50 kw. to the circuit external to its terminals,[1] and that 100 volts P. D. will be maintained at this output across the terminals. The

[1] The potential difference at the brushes and the terminals of shunt generators is practically the same, but in a series or compound-wound generator the potential at the brushes is higher than that at the terminals, on account of the I R drop in the series field, ¶¶ 300 and 303.

current, therefore, at full load will be, by Formula (55) 50,000 ÷ 100 = 500 amperes.

Owing to the electrical losses in the armature and fields the total kilowatts generated is higher than the machine's rating. For example, the 50-kw. machine alluded to may develop 55 kw., of which only 50 kw. can be utilized in the external circuit.

308. Losses in a Dynamo. — There are two classes of losses in a dynamo,

(1) *Mechanical losses,*
(2) *Electrical losses.*

(1) The mechanical losses include the friction between the rotating armature shaft and its bearings, windage, and the friction of the brushes upon the commutator. These friction losses are practically the same at all loads, and consume a certain percentage of the power supplied to the machine, which does not therefore appear as useful energy in the external circuit.

(2) The electrical losses include the I^2R losses in the armature and fields and at the brush contacts, the losses due to eddy currents (¶ 289) and hysteresis (¶ 293).

Losses in the field rheostat shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even in separately-excited machines. All the losses may be summed up then as due to

(*a*) *Mechanical friction,*
(*b*) *Electrical friction* (*resistance*),
(*c*) *Magnetic friction* (*hysteresis*).

309. Efficiency of a Generator. — The meaning of the term efficiency is given in ¶ 151. When the efficiency of a machine is stated without specific reference to load conditions, full or rated load is always to be understood. The efficiency of a generator is the ratio of the energy delivered by it to the energy supplied to it, or,

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}$$

The efficiency therefore considers the mechanical, electrical, and magnetic losses given in § 308. Its value varies with the size of the machine and the load it is supplying. For example, a 5-kw. dynamo may have as low an efficiency as 80 per cent; a well-designed 40-kw. machine, 90 per cent, and a 500-kw. generator, 94 per cent. Again a certain 200-kw. generator has an efficiency at full load of 93 per cent, at $\frac{3}{4}$ load of 92 per cent, at $\frac{1}{2}$ load of 90 per cent, and at $\frac{1}{4}$ load of 84 per cent.

TO OBTAIN THE EFFICIENCY OF A GENERATOR:

Divide the energy delivered by the generator by the output plus the sum of the mechanical, electrical, and magnetic losses.

Let P = output of generator in watts,

p = total losses of generator in watts.

Then the efficiency is

$$\text{efficiency} = \frac{P}{P + p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \textbf{(67) bis.}$$

Problem 124. — It requires 44 kw. (58 H. P.) to drive a 40-kw. generator. What is its efficiency?

Here P = 40 kw. and the input is P + p = 44 kw., whence by Formula (67)

$$\text{efficiency} = \frac{P}{P + p} = \frac{40}{44} = 0.91 = 91 \text{ per cent.}$$

Problem 125. — Determine the efficiency of the generater considered in Problem 123, if 14 kw. are required to drive the machine.

Input = 14,000 watts; output = 114 × 100 = 11,400 watts,

therefore $\quad \text{efficiency} = \frac{11,400}{14,000} = 0.81 = 81\%.$

With electrical machinery two efficiencies are recognized, *conventional efficiency* and *directly-measured efficiency.* Unless otherwise specified, the conventional efficiency is to be employed. Conventional efficiency of machinery is the ratio of the output to the sum of the output and the losses; or of the input minus the losses to the input; when, in either case, conventional values are assigned to one or more of these losses. The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practicably indeterminable, and must, in many

cases, either be approximated by an approved method of test, or else values recommended by the American Institute of Electrical Engineers and designated "conventional" values shall be employed for them in arriving at the conventional efficiency. To obtain the directly-measured efficiency, input and output determinations may be made directly, measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating-power method, sometimes known as "loading-back" method (¶ 315), may be used.

QUESTIONS

1. What is a shunt-wound generator, a series-wound generator, and a compound-wound generator?

2. Since the field magnets of a self-exciting generator are not supplied with current from any external source, how is it possible for the machine to generate?

3. A 110-volt incandescent lamp is connected to the terminals of a series machine running at its proper speed and capable of generating 4000 volts, yet the lamp fails to light. Why is this?

4. The main switch of a shunt generator is closed and then the machine started up, but it refuses to "build up." Why?

5. A large number of lamps are suddenly switched off from a circuit connected to a shunt generator. What two actions will immediately occur at the generator and how will you counteract them?

6. What are "residual volts"?

7. Give two reasons for the fall of potential at the brushes of a shunt generator when the current from it is increased.

8. What is the advantage of a compound-wound generator over a shunt machine?

9. What is the difference in the method of regulating the field magnetizing force of a series and of a shunt machine?

10. A generator is compounded for 10 per cent of its rated voltage. What is meant by this and how is it accomplished?

11. What is meant by an over-compounded generator?

12. Since an alternating current is not suitable for magnetizing field magnets, how can an alternator be self-exciting?

13. What is an exciter, and for what is it used?

14. What will be the effect of joining two shunt generators in series if one machine is rated at 50 kw. and the other at 100 kw.? Both machines have the same E. M. F.

15. What is an equalizing bar, and for what purpose is it used?

16. How would you proceed to parallel a compound-wound direct-current generator, which is "shut down," with two others that are carrying loads?

17. How would you disconnect and shut down one of the machines in Question 16?

18. Make diagrammatic sketches of all the different methods of field excitation with which you are familiar.

19. How may a shunt generator be designed to supply current to both sides of a three-wire distribution circuit?

20. Explain what determines the capacity of a dynamo.

21. What is meant by the efficiency of a generator?

PROBLEMS

1. The E. M. F. of a shunt-wound railway generator rises from 500 volts at full load to 590 volts upon disconnecting the load. What is the regulation of the machine in per cent? *Ans.* 18%.

2. A series dynamo has an armature resistance of 0.03 ohm and a field resistance of 0.01 ohm; the machine is connected to lamps requiring 11 amperes and having a resistance of 4 ohms; the resistance of the lead wires is 0.4 ohm. The generator requires 1½ H. P. to drive it. Find the following: (*a*) total E. M. F. generated, (*b*) P. D. at the brushes, (*c*) efficiency. *Ans.* (*a*) 62.16 volts; (*b*) 61.74 volts; (*c*) 77%.

3. A shunt dynamo is driven as a generator to supply 150 lamps, connected in parallel, each having a resistance of 60 ohms (hot), and requiring 0.85 ampere. The resistance of the armature is 0.02 ohm, of field magnets, 22 ohms; resistance of leads neglected. (*a*) Find the E. M. F. (*b*) What is the P. D.? *Ans.* (*a*) 53.596 volts; (*b*) 51 volts.

4. A compound-wound short-shunt generator is connected to 700 incandescent lamps in parallel, each having a resistance of 220 ohms (hot) and requiring 110 volts. Resistance of leads, 0.02 ohms, shunt field, 40 ohms, series field, 0.015 ohm, armature, 0.025 ohm. It requires 70 H. P. to drive the machine. Find the following: (*a*) E. M. F. generated, (*b*) P. D. at brushes, (*c*) drop on series field, (*d*) watts lost in shunt field, (*e*) watts lost on the line, (*f*) efficiency. *Ans.* (*a*) 131.076 volts; (*b*) 122.25 volts; (*c*) 5.25 volts; (*d*) 373.5 watts; (*e*) 2450 watts; (*f*) 78%.

5. The efficiency of a 175-kw. generator is 87.5 per cent. How much energy is supplied to the machine? *Ans.* 200 kw.

LESSON XXVI

DIRECT-CURRENT MOTORS

Comparison Between a Generator and a Motor — Direction of Rotation of Series and Shunt Motors — Position of the Brushes on a Motor — Counter Electromotive Force of a Motor — Current Taken by a Motor — Mechanical Power of a Motor — Torque — Output and Efficiency of Motors — Starting Motors — Speed Control of the Shunt Motor — Speed Regulation — Characteristic Curves of Motors — Electric Traction — Direct-Current Motor-Generator Sets — Motor Wiring Calculations — Installation of Interior Wiring — Questions and Problems.

310. Comparison Between a Generator and a Motor. — A generator is a machine for generating electrical energy by moving conductors in a magnetic field, the force necessary to main-

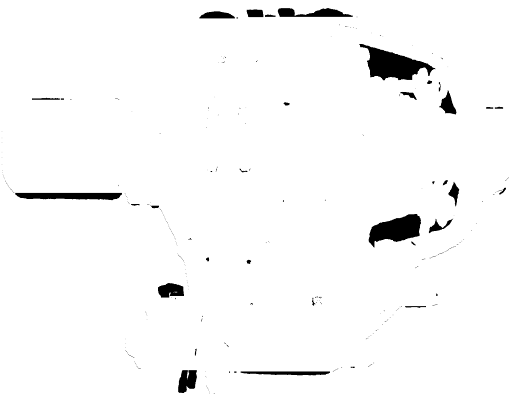


Fig. 375. — Multipolar Direct-current Motor.

tain the motion being supplied by a steam engine or other source of power. An electric motor is just the reverse, and is a machine for converting electrical into mechanical power. When the field magnets of a dynamo, as Fig. 375, are excited and a current is passed through its armature by means of the

brushes, the armature will revolve in the magnetic field. The rotation is due to the interaction between the magnetic field of the current-carrying wires upon the armature, and that produced by the field magnets. An electric motor, for direct currents, is constructed in the same manner as a generator. Any

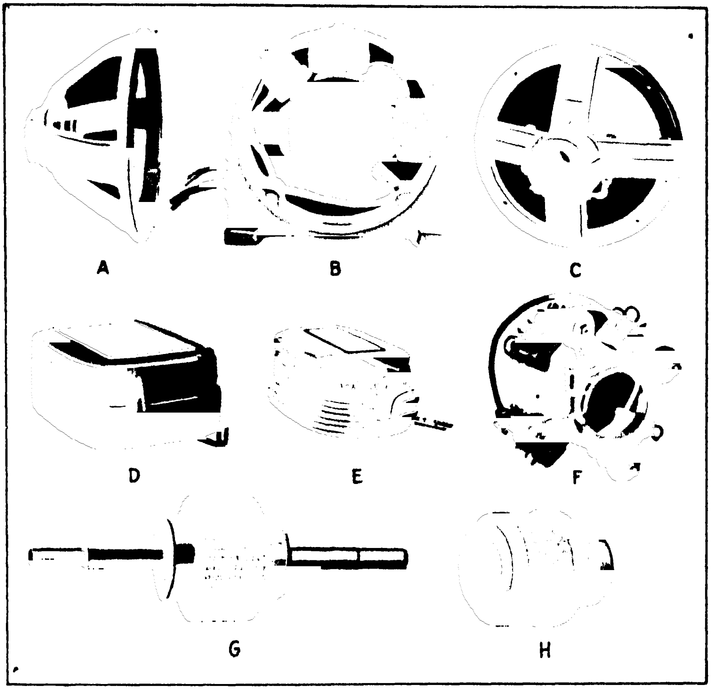


Fig. 376. — Dissected View of Type RC Shunt Motor.

machine that can be used as a generator will, when supplied with electrical power, run as an electric motor, and conversely, a motor, when driven by mechanical power, will supply electrical energy to the circuit connected to it. In fact, the terms generator and motor are applied to a dynamo to indicate the direction of energy conversion, whether from mechanical to electrical, or vice versa.

The previous lessons on the construction of generators will apply equally well to electric motors, although there are some differences in appearance imposed by the location of the machines. Motors are classified in the same manner as generators, and may be (a) *series wound*, (b) *shunt wound*, and (c) *compound wound*.

The general appearance of a direct-current motor is seen from Fig. 375, which shows a 20-H. P. motor made by the General Electric Co. A dissected view of this machine appears in Fig. 376, wherein the principal parts can be more clearly seen

List of Principal Motor Parts, Fig. 376.

A — Shield at commutator-end of machine.

B — Frame of 4-pole motor showing three main (large) poles and two commutating poles in place. One pole of each kind is illustrated without its coil.

C — Shield at pulley-end of machine.

D — Main (shunt) field coil of insulated wire wound on horn-fiber spool.

E — Commutating field coil.

F — Brush-holder yoke, brushes and brush holders.

G — Armature core of laminated steel disks clamped together and keyed to shaft; recessing is for binding wire which keeps armature wires in slots.

H — Commutator built up of many copper segments separated by mica strips.

311. Direction of Rotation of Series and Shunt Motors. — If the polarity of the field magnets and the direction of current flow through the armature of a motor are known, the direction of rotation of the armature can be determined by the left-hand rule, page 218 (see also Fig. 323).

A series dynamo when supplied with current becomes a *series motor*, Fig. 366, and will run in the opposite direction to its motion as a generator. Reversing the direction of current at its terminals will not change the direction of rotation, since the current will still flow through the armature in the same direction as through the field. It is necessary to reverse *either* the armature or field connections to change the direction of motion.

A shunt dynamo runs in the same direction when used as a *shunt motor* as when used as a generator. This will be seen from Fig. 363; if a current from an external source enters by the lower brush it will flow up through the armature in the same direction as when it is used as a generator, but the current through the fields will be reversed from the direction indicated in the figure, since the fields are in parallel with the brushes.

Experiment 103. -- Connect and operate the student's experimental dynamo, Fig. 312, as a shunt motor. Reverse the current at the motor terminals and the direction of rotation will be found the same as before. Why? Now reverse the direction of rotation, ¶ 189

Experiment 104. Connect the armature of the motor used in Experiment 103 in series with the two field coils in parallel, so that the poles have the proper polarity, **N** and **S**. It is now a series motor (a) Apply the left-hand rule, page 218, for the direction of rotation of the armature. (b) Reverse the direction of rotation.

312. Position of the Brushes on a Motor. The reaction of the armature current upon the field of a motor distorts that field just as in a generator, ¶ 294, except that the lines of force are now crowded together in the leading pole tips and lessened in the trailing tips, so that the flux distribution is just opposite to that illustrated in Fig. 346. The commutation plane will, therefore, advance backward against the direction of rotation of the motor, and it is at this position that commutation in a motor should take place. The brushes are set in the same manner as given for a generator in ¶ 295, but are *rocked backward against the direction of rotation* until the non-sparking position is found. The angle of advance against the direction of rotation will increase as the current taken by the motor increases, or as the work it is required to perform increases, and decrease as the load is removed. In motors with interpoles or compensated windings (¶ 296) the brushes may be retained in the same position with variations in load. The conditions and remedies for the sparking at the brushes of a motor are the same as those given in ¶ 297.

313. Counter Electromotive Force of a Motor. — The wires of a motor armature, rotating in its own magnetic field, cut the lines of force just as if it were being driven as a generator, and consequently there is an induced E. M. F. in them. By

applying the right- and left-hand rules to the single coil in Fig. 377, it will be seen that if it is rotated counter clockwise by a prime mover, the direction of the induced E. M. F. will tend to send a current around the coil from D to C, to B, to A, while when supplied with current as a motor, to rotate in the same direction, the applied voltage will oppose the induced pressure and cause a current to flow from A to B, to C, to D. This induced pressure in a motor is called its *counter electromotive force* (sometimes abbreviated C. E. M. F.) and is always in such a direction as to oppose the pressure applied to the motor terminals, or to that of the supply mains. The dotted arrows, in Fig. 377, indicate the direction of the counter E. M. F., and the solid arrows, that of the applied E. M. F. as found by the right- and left-hand rules. A motor, without load, will run at such speed that its counter E. M. F. will very nearly equal the applied pressure.

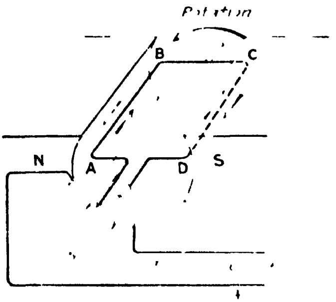


Fig. 377 Single-coil Armature of Bipolar Motor.
Full arrows show applied E. M. F., while dotted arrows show direction of counter E. M. F.

The counter E. M. F. of a motor running at any speed will be the same as when it is run as a generator at this speed, provided the field strength is the same in both cases, hence to find the counter E. M. F. of a motor at any speed, run it as a generator at this speed and measure the induced E. M. F. by a voltmeter. The presence of a counter E. M. F. may also be observed by connecting a lamp across the terminals of a shunt motor, running without much load, and opening the main supply circuit. The lamp will remain illuminated and gradually become dim as the speed of the motor decreases. A voltmeter connected across the motor terminals will also indicate, by the direction of deflection of the pointer, that the counter E. M. F. is opposed to that of the line E. M. F. when the supply switch is opened.

The counter E. M. F. in a motor can never equal the applied

E. M. F., but is always less by an amount equal to the drop in the motor armature, (I × r). The difference between a dynamo operating as a generator and as a motor is as follows:

Generator	Motor
The armature is driven by outside mechanical power in a magnetic field and an E. M. F. is induced in it which sets up a current in the external circuit.	The armature is supplied with current from an outside source and the interaction of the fluxes from armature and field causes rotation of the armature.
This current occasions an electrodynamic force which opposes the motion of armature. The work done by the prime mover in overcoming this opposition is the work which maintains the current in the generator circuit.	This rotation occasions a counter E. M. F. in the armature which opposes the current supplied. The work done by the outside source in overcoming this C. E. M. F. is the work which appears as mechanical energy at the motor pulley.

To find the current flowing through the armature of a motor:

Subtract the counter E. M. F. from the applied E. M. F. and divide this result by the armature resistance. Ohm's Law for a motor is as follows:

Let

E = E. M. F. applied at motor brushes,
$\mathcal{E}$ = counter E. M. F. developed by motor,
I = current through motor armature,
r = internal resistance of motor armature.

Then

$$I = \frac{E - \mathcal{E}}{r} \qquad (102).$$

The speed which any motor attains is such that the sum of the counter E. M. F. developed and the drop in the armature is exactly equal to the applied E. M. F. This is expressed by the following formula derived by transposition from Formula (102):

Counter E. M. F. + (I × r) = applied E. M. F.,

or $$\mathcal{E} + (I \times r) = E \qquad (103).$$

The voltage drop in the armature of a motor is a small percentage of the applied pressure, perhaps about 2 per cent of the terminal pressure in a 500-kw. motor and about 5 per cent in a

1-kw. motor, so that the counter E. M. F. is not much different from the applied E. M. F. Since the power driving a motor equals the applied pressure times the current, most of which is usefully expended in mechanical output, the counter E. M. F. is an essential and valuable feature of the motor, rather than a detriment to its operation.

TO FIND THE COUNTER E. M. F. OF A MOTOR:

Multiply the resistance of the armature by the current flowing through it and subtract this product from the E. M. F. applied to the motor brushes. The Formula is derived by transposition of Formula (103):

$$\mathcal{E} = E - (I \times r) \quad \ldots\ldots\ldots \quad \textbf{(104)}.$$

The counter E. M. F. of a motor depends upon the same factors as those governing the induced E. M. F. in a generator, and is directly proportional to:

(*a*) *the number of lines of force cut,*
(*b*) *the number of conductors upon the armature,*
(*c*) *the speed at which the lines of force are cut.*

Problem 126. A small motor is connected to a 110-volt circuit; the counter E. M. F. at a particular speed is 100 volts, the resistance of the armature is 2 ohms. What current is being supplied to the motor?

By Formula (102) $I = \frac{E - \mathcal{E}}{r} = \frac{110 - 100}{2} = 5$ amperes.

Problem 127. The armature resistance of a shunt-wound motor is 0.5 ohm, and at a certain load 10 amperes flow through it; the voltage at the motor brushes is 110 volts. What is the counter E. M. F.?

By Formula (104) $\mathcal{E} = E - (I \times r) = 110 - (10 \times 0.5) = 105$ volts.

Problem 128. What current would the motor referred to in Problem 126 receive if it had no counter E. M. F.?

By Formula (27) $I = \frac{E}{R} = \frac{110}{2} = 55$ amperes.

314. Current Taken by a Motor.—The current taken by a motor depends upon the mechanical load that it carries; the larger the load, the greater the current. This accommodation of current to load results in economical operation, and depends upon counter electromotive force. There is no counter E. M. F. induced in a motor armature until it begins to revolve, so that the current flowing through it, when stationary, is equal to

E ÷ R, as in Problem 128. When the armature begins to rotate, the current through it gradually diminishes, since the counter E. M. F. rises with the speed. It requires more energy to start a motor than to maintain it at any particular speed, ¶ 135, so that the counter E. M. F. automatically acts like resistance in a circuit, and decreases the current as the speed increases.

If the load upon a motor be increased the force that it was developing is no longer sufficient to overcome the new load and consequently its speed falls. The reduction of speed lessens the counter E. M. F. and thus permits a greater current to flow through the armature, which greater current produces a greater force. The automatic adjustment of the current to the load is shown in the following experiment:

Experiment 105. — An ammeter is connected in series with the armature of a small motor and the current was noted for several speeds, which were read from a speed indicator or tachometer, as follows:

Motor Test.

Speed Revolution per minute	Amperes	Speed Revolutions per minute	Amperes
0	20.0	1600	7.8
500	16.2	1800	6.1
1000	12.2	1950	5.1

At the maximum speed the motor in the above test receives 5.1 amperes, or about one-fourth of the current which would flow through it at rest. If some machinery be now connected to the motor pulley by a belt, the motor will slow down somewhat, thus decreasing the counter E. M. F. and permitting more current to flow through the armature to perform the extra work. When the load is removed the motor increases in speed, thus increasing the counter E. M. F. and decreasing the current taken from the line. There is thus a continual automatic adjustment between the current supplied to a motor and the work it has to perform, or *the electrical power taken from the supply mains by a motor is directly proportional to the mechanical power it is required to develop at its pulley.* The speed of a shunt motor, running fully loaded, may be only 5 per cent less than the speed the motor attains when running idle.

TO FIND THE MECHANICAL POWER DEVELOPED BY A MOTOR:

Multiply the counter E. M. F. by the current through the armature.

$$P = \mathcal{E} \times I \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (105).$$

The mechanical power developed includes that required for mechanical friction losses and the power which is expended in eddy currents and hysteresis.

Problem 129. — (a) What power is developed by a small 110-volt motor whose armature resistance is 2 ohms and which runs at a speed such as to develop a C. E. M. F. of 100 volts? (b) What power is supplied to the motor?

By Formula (102) $I = \frac{E - \mathcal{E}}{r} = \frac{110 - 100}{2} = 5$ amperes (Problem 126).

By Formula (105) $P = \mathcal{E} \times I = 100 \times 5 = 500$ watts (a).
By Formula (54) $P = E \times I = 110 \times 5 = 550$ watts (b).

315. Mechanical Power of a Motor – Torque. — The mechanical power of a motor depends upon two factors, the speed and the torque, and is equal to the product of these factors. The term "torque" is applied to the twisting force which is produced in the armature when a current is sent through it, and represents the effort made to cause rotation. This effort is made up of two components; first, the pull, measured in pounds, and second, the length of arm at which this pull acts, measured in feet. Thus, a pull of 50 pounds acting at a distance of 2 feet would cause a torque of 100 lbs.-ft.

The most common method of testing the mechanical output of a motor is with the Prony brake, Fig. 378. The brake consists of a lever arm of wood hollowed out to fit the pulley and clamped to it by bolts passing through a wooden block on the other side of the pulley. The bolts are fitted with wing nuts, by means of which the pressure on the surface of the pulley can be adjusted, thus altering the force due to friction, and the pull at the end of the lever arm. By measuring this pull, the speed of rotation, and the length of the lever arm, the power developed can be readily calculated.

Method. — The principle of the brake is quite simple, for it is evident that due to the friction of the clamp on the motor pulley there is a tendency to make the lever arm rotate. The tendency to rotate is measured by

means of a platform scale, the lever arm resting on a V-block on the platform of scales, or by means of a spring balance as in Fig. 378, the direction of the balance being perpendicular to the brake arm. Work is equal to the product of force and distance, that is, W = F × r, ¶ 138, where r is the distance from the center of the shaft to the point of application of the force resisting the tendency of the lever to rotate. In one revolution of the pulley, the brake arm if allowed to rotate with it would describe a circle having a radius r feet (length of arm, Fig. 378), the distance then through which the point of application of the force would travel would equal $2\pi \times r$,[1] and if the number of revolutions per minute is n, the power, in foot-pounds per minute, is Power = $2\pi r n F$, where F equals the force of the pull in pounds. To reduce this to horse-power, it is necessary to divide by 33,000, since one mechanical horse-power equals 33,000 ft.-lbs. of work per minute (¶ 139), or

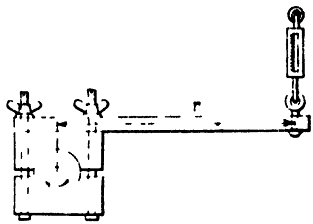


Fig. 378. — Prony Brake.

$$\text{H. P.} = \frac{2\pi r n F}{33{,}000} \quad \text{. . . . . (106).}$$

In testing the output of large motors, they are coupled to available generators, the output of which is absorbed by suitable resistances. If the generators happen to develop the same voltage as that of the circuit supplying the motor the current from the generators may be returned to the supply circuit, thereby saving considerable power. The amount of load in this method, called the *loading-back method,* is regulated by altering the strength of the generator fields.

316. Output and Efficiency of Motors. — The capacity of a motor to perform useful work is limited by the same conditions as those governing the capacity of a generator, ¶ 306. Motors are commercially rated according to the amount of power they will maintain at full load, at their pulleys, within the limit of permissible heating. For example, a 10-kw. 110-volt motor will, when supplied with 110 volts at its terminals, develop 10 kw. or 13.4 horse-power at the pulley. The efficiency of a motor, as in the case of the generator, ¶ 309, is

[1] The Greek letter π (pi) represents the relation between the diameter of a circle and its circumference, and is equal to 3.1416. Circumference of a circle = $\pi \times d$, where d is the diameter.

the ratio of the output to the input. The energy furnished to the motor is readily measured, and from this must be subtracted the losses in the motor to obtain the available energy. These losses are divided into two classes: the I^2R losses in the armature and fields, and the stray power loss, which includes friction, eddy currents and hysteresis. Therefore,

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}} \quad . \quad . \quad . \quad . \quad . \quad \textbf{(107)}.$$

Consider a 25-H. P., 220-volt, shunt-wound motor, having an armature resistance of 0.1 ohm and a field resistance of 80 ohms, to operate under heavy load. Its speed at this load is such as to develop a counter E. M. F. of 210 volts. The drop in the armature is the difference between the applied voltage and the counter E. M. F., or 220 − 210 = 10 volts. The armature current is 10 ÷ 0.1 = 100 amperes, and the field current is 220 ÷ 80 = 2.75 amperes. The power consumed in copper loss is 10 × 100 = 1000 watts in the armature and 2.75 × 220 = 605 watts in the shunt field. If the stray power loss be taken as 600 watts, then the total loss in the machine is 1000 + 605 + 600 = 2205 watts.

The input to the motor is 100 × 220 = 22,000 watts for the armature and 605 watts for the field, or a total of 22,605 watts. Whence the efficiency by Formula (107) is

$$\text{efficiency} = \frac{22{,}605 - 2205}{22{,}605} = \frac{20{,}400}{22{,}605} = 0.903 = 90.3\,\%.$$

The motor output is $\dfrac{20{,}400}{1000} = 20.4$ kw. or $\dfrac{20{,}400}{746} = 27.4$ H. P.

317. Starting Motors. — The resistance of the armatures of motors is very low; for example, the armature of the 220-volt 25-H. P. shunt motor of ¶ 316 has a resistance of 0.1 ohm. If this motor were directly connected to the supply mains, a much greater current than that required for full load would flow through it before any counter E. M. F. could be developed, resulting in damage to the windings; the low resistance would practically short-circuit the mains, causing an excessive drop of voltage. See Problem 128. For this reason a rheostat, called a

starting box, Fig. 379, is always inserted in the armature circuit of a shunt motor to limit this current before the motor attains its speed. The value of resistance in the starting rheostat should be such that, when added to the armature resistance, it would permit the motor to take a current not much larger than its full-load value. As the motor attains some speed, and counter E. M. F., this resistance is gradually cut out by moving arm S from post 1, to 2, to 3, etc., until at point 5 the armature is directly connected across the line. For example, to start the shunt motor, close switch A, when the motor fields will be excited; move the arm S of the starting box to point 1, when the armature circuit will be completed through the starting resistance; cut out the starting resistance as the motor attains speed by gradually moving S to point 5. To stop the motor, open the main switch A, and then place the arm of the starting box on the off position, so that the motor will be ready for re-starting.

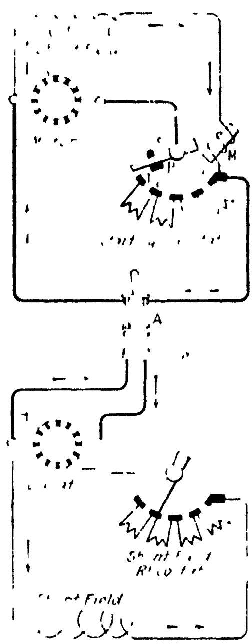


Fig. 379 – Connections of a Shunt Motor to a Generator Circuit

In an *automatic motor starting box*, such as that depicted in Fig. 65, the arm S carries a small piece of iron, shown at P in Fig. 379, and turns against the action of a spring; an electromagnet M, in series with the shunt field, is mounted on the box, and when arm S rests on point 5 it is held there by the electromagnet against the action of the spring. The advantage of this arrangement is that, if for any reason the main power supply circuit should be interrupted, the starting box arm will automatically open the circuit and shut down the motor, instead of permitting the motor armature to cause a short-circuit across the mains when the power is again turned on.

In starting a shunt motor always be sure that the fields are first

excited (test their attractive power with a penknife), since without the field excitation the armature, in its efforts to generate a counter E. M. F., would speed up to a dangerously high value and possibly be wrecked.

Series motors are also equipped with starting resistances, in the form of a controller, which is gradually moved to cut out resistance, as with shunt motors.

318. Speed Control of the Shunt Motor. — In many motor applications it is necessary to alter the speed of the motor.

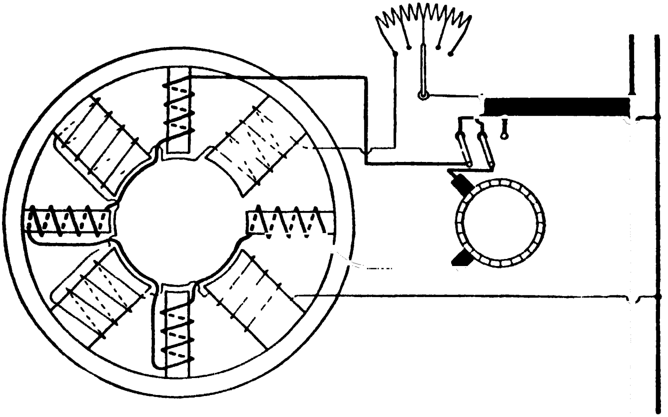


Fig. 380. -- Wiring Diagram of Four-pole Interpole Motor.
Interpole coils are in series with the armature

This is usually accomplished in shunt motors by varying the strength of the magnetic field. Sometimes in experimental work a variable resistance is introduced into the armature circuit, but this method of speed control is wasteful of energy and speed changes occur with variations of load. Again, the speed of shunt motors may be changed by altering the E. M. F. impressed upon the armature. This method is employed in machine shops for driving lathes, planers, drill presses, etc., and requires multi-voltage supply circuits.

Returning to the usual method of speed control, namely magnetic field variation, it must be remembered that the stronger the field the lower will be the speed necessary for the develop-

ment of counter E. M. F. for a given load. To make a shunt motor speed up it is necessary to weaken its field. The strength of the magnetic field may be varied, 1, by altering the current in the field coils, and 2, by altering the magnetic reluctance of the path of lines of force.

1. The current in the field coils can be varied by placing a rheostat in the field circuit. Increasing its resistance lessens the current and weakens the field, and consequently the motor speeds up. The control of speed by varying the field strength is limited in range of action, since on one hand saturation of the magnetic circuit requires large field currents which cause undue heating, and on the other hand, with low field strengths, armature reaction produces a considerable demagnetizing and distorting effect on the field flux and occasions sparking. However, the range can be vastly improved by neutralizing the effects of armature reaction, ¶ 296, by means of compensating windings and interpoles. Fig. 380 shows the connections of an interpole (or commutating-pole) motor. Such interpole or compensated motors afford sparkless commutation under wide ranges of speed and load, and are splendidly adapted for individual motor drive of machine tools, for elevator operation, for driving printing presses, and for many other applications where large speed variations are essential.

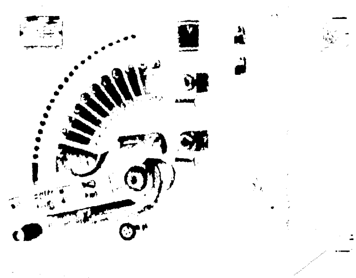


Fig. 381. Combined Starting Box and Field-regulating Resistance.

Cutler-Hammer Mfg. Co

A combined starting and field-regulating rheostat is shown in Fig. 381. The movable arm has two parts which wipe over separate sets of contacts. The motor is started by moving the handle to the extreme right, where the magnet will hold one part of the arm. The other part is then moved back and will make contact with the studs connected with the field resistance and thus alter the speed of the motor to any desired value.

2. The speed of a shunt motor may be varied by altering the reluctance of the path of flux, usually by varying the length of the air gap between the armature and the field poles. Increasing the gap length, decreases the flux and therefore produces a higher speed. This method is utilized in motors made by the Stow Manufacturing Company, in which the iron poles are simultaneously moved through hollow field cores by means of a hand wheel. It is also utilized in motors made by the Reliance

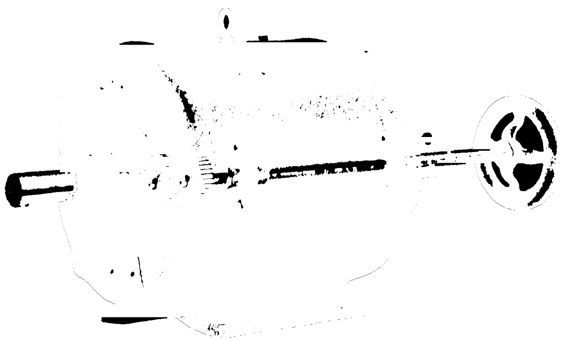


Fig. 382.--Reliance Adjustable-speed Motor.

Electric and Engineering Company, in which the width of the air gap is different at the two ends of the machine, and speed variation is accomplished by an axial movement of the armature with respect to the field. Fig. 382 shows a Reliance semi-enclosed motor in which the speed is adjusted by moving the armature by the hand wheel.

319. Speed Regulation. – The speed of a shunt-motor under constant impressed voltage and fixed excitation will be approximately constant. The speed will fall somewhat as the load on the machine is increased because of the increased armature drop. This change of speed, with a definite setting of the field rheostat, occurring from full load to no load, expressed as a percentage of the speed at no load, is called the *speed regulation* of the motor.

$$\text{Speed regulation} = \frac{\text{no-load speed} - \text{full-load speed}}{\text{no-load speed}} \quad . \; . \quad \textbf{(108)}.$$

Speed regulation concerns itself with changes in speed inherent in the machine, whereas speed control signifies deliberate external adjustment to attain various desired speeds; care should be exercised not to confuse these terms.

Problem 130. – A motor when operating at full load runs at 1700 rev. per min. and when the load is removed its speed is 1800 rev. per min. What is its speed regulation?

By Formula (108),

$$\text{speed regulation} = \frac{1800 - 1700}{1800} = 0.056 = 5.6\%.$$

When the numerical value of the speed regulation of a motor is small, as in the foregoing problem, the motor is said to possess good speed regulation.

Series motors operated from constant-potential mains are distinctly variable-speed motors. They have a low speed under large load and a high speed under light load. If the load were removed from a series motor it would speed up tremendously and perhaps be ruined; such motors are consequently solidly coupled to their loads, by gears rather than belts. Fig. 383 depicts a Type CO2-500 General Electric Co. series-wound, reversible, totally-inclosed motor for operating cranes and hoists. It is equipped with a shoe-type solenoid brake for holding the load at any position.

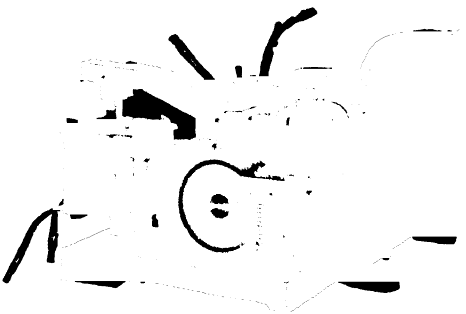


Fig. 383. — Series-wound Crane Motor.
Made in sizes up to 240 H P.

320. Characteristic Curves of Motors. — In selecting a motor for performing a definite service it is desirable to know its performance characteristics at various loads. In shunt motors one is interested in the speed, current input, torque exerted, and efficiency for various outputs, and this information

is usually embodied in curves plotted on cross-section paper and supplied by the manufacturer. Fig. 384 shows the characteristic curves of a 7.5-H. P., 230-volt, Type RC General Electric Co. commutating-pole shunt motor. Illustrations of this machine are given in Figs. 375 and 376.

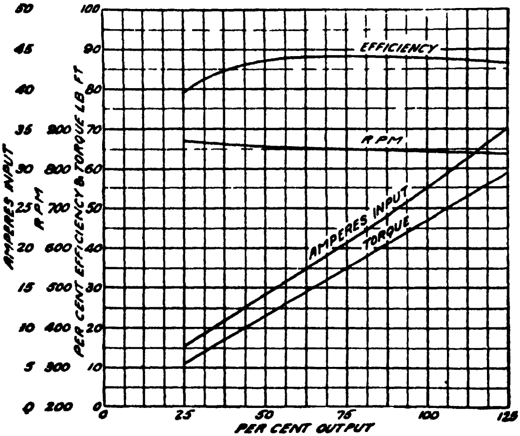


Fig 384. — Characteristic Curves of a Shunt Motor.

Reading from this curve for only three different loads,

Load	Current	Torque
25 % full load	7.7 amperes	11 lb.-ft.
50 % " "	14.1 "	23 "
100 % " "	27.5 "	47 "

it is seen that both the current and the torque of this shunt motor increase nearly proportional to load. Per ampere of current there is produced a torque of $\frac{11}{7.7} = 1.4$ lb.-ft. at $\frac{1}{4}$ load, $\frac{23}{14.1} = 1.6$ lb.-ft. at $\frac{1}{2}$ load, and $\frac{47}{27.5} = 1.7$ lb.-ft. at full load; showing that the torque exerted by the motor is very nearly proportional to the current taken.

The series motor presents quite different characteristics for it was stated in ¶ 319 that with increased load the speed of a series motor decreases. This is shown in Fig. 385, which gives the speed, torque, and efficiency curves of a GE-247 commutating-pole, 600-volt, 10-H P (one hour rating[1]) series rail-

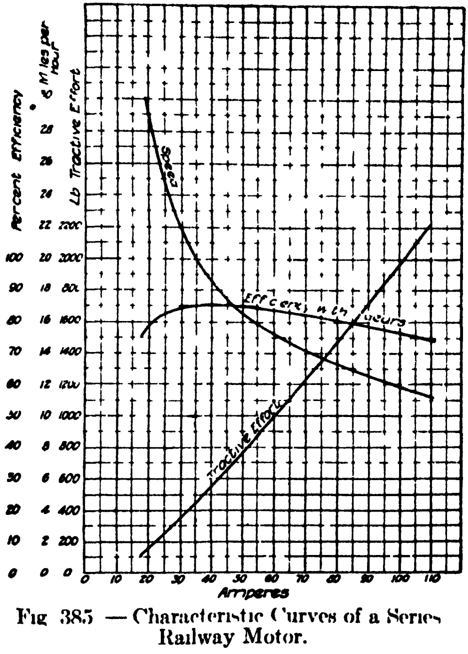


Fig 385 — Characteristic Curves of a Series Railway Motor.

Diameter of car wheels is 30 in gear ratio [illegible] = 4 2

way motor. This motor is illustrated in Fig. 386. The torque curve is marked *tractive effort* in the diagram, tractive effort being the force exerted by a railway motor on the car in the

[1] Nominal rating of a railway motor is the mechanical output at car axle which causes a temperature rise above surrounding air, by thermometer, not exceeding 90° Centigrade at the commutator and 75° Centigrade at any other normally accessible part after one hour's continuous run at rated voltage on a stand with the motor covers arranged to secure maximum ventilation without external blower.

direction of its motion. The relation between tractive effort in pounds and torque in lb.-ft., neglecting losses in gears, is given by

$$\text{tractive effort} = \frac{24 \times \text{gear ratio} \times \text{torque}}{\text{wheel diameter in inches}} \quad . \quad . \quad . \quad . \quad (109).$$

The relation between car speed in miles per hour and motor speed in rev. per min. is given by

$$\text{miles per hour} = \frac{\text{torque} \times \text{motor speed}}{14 \times \text{tractive effort}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (110).$$

Reading tractive effort and speed from the curve for three current values,

Current	Tractive Effort	Speed
25 amperes	250 lbs.	24.9 miles per hr.
60 "	1000 "	15.2 " " "
90 "	1700 "	12.5 " " "

it is seen that small torque is exerted by a series motor at high speed and vice versa. Since power output equals the product of torque and speed, the series motor draws a more uniform amount of energy from the line than does the shunt motor. Thus, from the foregoing table, while the tractive effort varies from 250 to 1700 lbs., a 7-fold increase, the product of tractive effort and speed increases from 6230 to 21,200, a 3.5-fold increase of power. On the other hand, a shunt motor would demand a 7-fold increase of power. For this reason the series motor is particularly well suited for car propulsion and for the operation of cranes, hoists and rolling mills.

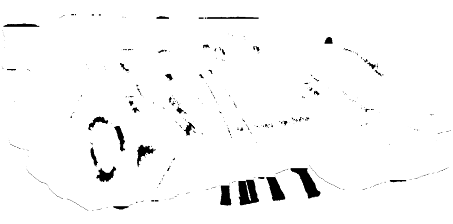


Fig. 386. — Series Railway Motor GE–247.
Frame has bearing in front which runs on wheel axle. Gear case is shown at the right.

Compound-wound motors in which the series and shunt fields assist each other are frequently used for heavy intermittent loads, such as in operating elevators, rolling mills, etc. They exert a powerful starting torque and yet the speed is not excessively variable under load variations.

321. Electric Traction. Series motors are used for railway work because they best fulfill the requirements, namely powerful torque at starting, variable speed and economical operation at varying loads. When two motors are used on a car their armatures and field coils are connected in series with each other and a resistance, which prevents too great a rush of current from the mains when the car starts. As the car gains headway a rheostat and switch, termed a *series-parallel controller* gradually cuts the resistance out of circuit until the motors operate in series on full voltage, then places the motors in parallel with a resistance in series with both, then gradually cuts out this resistance step by step until, finally, it connects each motor directly across the mains, or between the overhead trolley and the track: one terminal of the station generator being connected to the trolley and the other to the track.

On a level road the tractive effort to be exerted by a motor in order to drive the car at constant speed varies with a number of conditions, such as road bed, track, lubrication of journals, wind pressure, etc., collectively considered as train resistance. *The tractive effort varies directly as the weight of the car with passengers.* For average conditions about 20 pounds tractive effort are required for each ton propelled by the motor on a level road, with a speed of from 20 to 40 miles per hour. For example, to propel a car weighing 20 tons, with passengers aboard weighing 3 tons, will require a tractive effort on a level of $(20 + 3) \times 20$ or 460 pounds. In general the tractive effort in pounds to be exerted by a motor in propelling a car of W tons weight against train resistance is

$$\text{tractive effort (resistance)} = 20\,W \quad . \; . \; . \; . \; . \quad \textbf{(111)}.$$

When the car ascends a grade a certain amount of *additional energy is required to propel it*, and this is represented by the amount of energy required to raise the car through the distance it travels vertically.

Grades are designated by the rise in feet per 100 feet traveled; thus a 4% grade means a vertical rise of 4 feet in a horizontal distance of 100 feet. The tractive effort which is necessary to propel each ton of car weight up a one per cent grade is $\frac{1}{100} \times 2000 = 20$ pounds, consequently if a car of W tons weight is to be drawn up a grade of g per cent with uniform speed then the tractive effort in pounds is

$$\text{tractive effort (grade)} = 20Wg \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (112).$$

The greatest amount of force required in railway operation however, is that necessary to *accelerate the car* from standstill. It takes a tractive effort of about 100 pounds to accelerate each ton of car weight at the rate of 1 mile per hour per second. Therefore to accelerate a car of W tons weight at the rate of A miles per hour per second requires a tractive effort (in pounds) of

$$\text{tractive effort (acceleration)} = 100\,WA \quad . \quad . \quad . \quad (113).$$

Consider a 20-ton car equipped with two series motors of the type shown in Fig. 386, whose characteristic curves are presented in Fig. 385. If this car shall start on a level track with a velocity increase every second of 1.5 miles per hour then a tractive effort is required which, by combining Formulas (111) and (113), is

$$\text{tractive effort} = 20 \times 20 + 100 \times 20 \times 1.5 = 3400 \text{ pounds.}$$

Each motor must exert half of this or 1700 pounds, which from Fig. 385 demands a current of 90 amperes. This current may be kept fairly constant by the controller while the car is accelerating until the two motors are each operating on the full line voltage of 600, which occurs when the speed of the car is 12.5 miles per hour (from same diagram). Thereafter the speed increases less rapidly because the current decreases as the car speeds up and this results in a lower available tractive effort; this reduction of the acceleration rate continues until eventually the speed of the car becomes constant. This constant speed will be that for which the available tractive effort is equal to the train resistance per motor, which is $\frac{20 \times 20}{2} = 200$ pounds, the speed being 27 miles per hour, Fig. 385.

322. Direct-Current Motor-Generator Sets. — For some purposes two (and sometimes more) dynamos are firmly coupled together as a unit, one machine acting as a motor and the other as a generator. Motor-generator sets may comprise, 1, direct-current machines, 2, alternating-current machines, and 3, both direct- and alternating-current machines. The first class includes *balancers* for maintaining the potential of the middle wire of three-wire systems, and *voltage-changing sets* for battery charging, electrolytic work, welding, voltage boosting, etc. The second and third classes are considered in § 375 Lesson XXX.

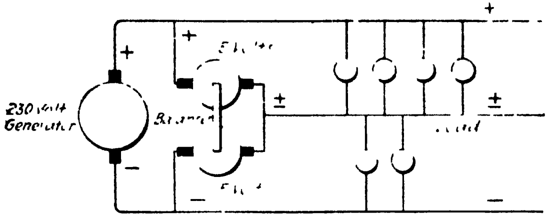


Fig. 387 — Motor Generator Used as a Balancer on a Three-wire Circuit.

A balancer associated with a three-wire distribution circuit is shown in Fig. 387 with its two dynamos connected in series across the generator leads. If the circuit is unbalanced and supplies a heavier load on say the upper side, the voltage on the lower side tends to become higher than on the other and the lower dynamo of the balancer will operate as a motor and drive the upper dynamo as a generator, which then assists in supplying current to the greater load on the upper side; this action takes place automatically. These machines usually have shunt or compound excitation and are rated by the amperes carried in the neutral wire.

323. Motor Wiring Calculations. — TO FIND THE CURRENT REQUIRED BY A MOTOR WHEN THE OUTPUT, EFFICIENCY, AND VOLTAGE ARE KNOWN:

If the output of the motor is expressed in kilowatts (kw.), *multiply the kw. rating by* 1000 *and divide by the voltage of the motor and by its efficiency, Formula* (114). If the output is ex-

pressed in horse power, *multiply the H. P. by 746 and divide this product by the voltage of the motor and by its efficiency, Formula* (115).

$$I = \frac{kw. \times 1000}{E \times \%\ M} \quad \ldots\ldots\ldots\ldots \quad (114).$$

$$I = \frac{H.\ P. \times 746}{E \times \%\ M} \quad \ldots\ldots\ldots\ldots \quad (115).$$

where E = voltage required by the motor,
kw = kilowatt rating of the motor,
H. P. horse power of the motor,
% M efficiency of the motor, expressed as a decimal.

TO FIND THE SIZE OF WIRE, IN CIRCULAR MILS, NECESSARY TO TRANSMIT ENERGY TO A MOTOR OVER ANY DISTANCE, WHEN THE VOLTAGE AND EFFICIENCY OF THE MOTOR ARE KNOWN:

Multiply the rated horse power of the motor by 746, then by the length of the circuit in feet and then by 10.79; divide this result by the product of the voltage required by the motor, the drop on the line and the efficiency of the motor, Formula (116).

Letting e be the voltage drop there results from combining Formula (115) with Formula (99),

$$C.\ M. = \frac{H.\ P. \times 746 \times L \times 10.79}{E \times e \times \%\ M} \quad \ldots\ldots \quad (116).$$

Problem 131. What size of wire is required to conduct current to a 220-volt 5-H. P. motor located 150 feet from the meter; the drop on the line is to be 5 volts and the efficiency of the motor is 80%? What current does the motor take?

By Formula (115) $I = \frac{H.\ P. \times 746}{E \times \%\ M} = \frac{5 \times 746}{220 \times 0.80} = 21$ amperes.

By Formula (116)

$$C.M. = \frac{H.P. \times 746 \times L \times 10.79}{E \times e \times \%\ M} = \frac{5 \times 746 \times 150 \times 2 \times 10.79}{220 \times 5 \times 0.80} = 13{,}720.$$

From Table VI, page 67, No. 8 B. & S. has a sectional area 16,510 C. M. The motor requires 21 amperes, and from Table XIII, page 306, the carrying capacity is 35 amperes; therefore No. 8 is the proper size of wire.

324. Installation of Interior Wiring. — All interior wiring must be installed in such a manner, that it will be protected from mechanical injury, and be safe as regards fire hazard or danger

to life; therefore wherever wires are installed in buildings the method of installation must conform to the rules of the National Board of Fire Underwriters as set forth in its "National Electrical Code." This Code is in effect throughout the United States and Canada, and gives definite rules for the installation of all kinds of wiring. It also specifies carefully the kind of material, such as wire, conduit, fuses, etc., that may be installed. Copies of the code will be found useful for reference and may be obtained by applying to any of the Fire Underwriters' offices.

Installation of wiring for light or power service, at voltages not exceeding 500 volts, may be done by any one of the following plans, all of which are approved by the code, but the use of some of them is restricted to special places:

Open or Exposed Wiring. — Wires are supported on porcelain knobs or cleats; the knobs or cleats should separate the wires about $2\frac{1}{2}$ inches and should be $\frac{1}{2}$ inch from the surface along which they run.

Concealed, Knob and Tube. — Wires are concealed between floor beams and studs of a building, knobs being used to support wires when run parallel to beams or studs and porcelain tubes when run at right angles through the beams or studs.

Molding Work. — Wires are run in a wood or metal molding. The metal molding consists of a sheet steel trough or backing and a steel cover which is snapped on the backing after wires are in place. Wood molding consists of a backing with grooves for the wires and a capping which is nailed to the backing after the wires are in place; this molding is made for two wires and for three wires. Molding work is particularly adapted to the wiring of buildings after their completion and has the advantage of cheapness, simplicity and accessibility.

Rigid Conduit. — Wires are run in unlined conduits which are free from scale on the inside and are coated with enamel inside and outside; the outside is sometimes galvanized when used where the pipe is exposed to the weather. Conduits must be continuous from outlet to outlet, at which places metal junction boxes made for the purpose are located; the conduit must properly enter and be secured to all fittings, and the system must be mechanically strong. Conduit affords the best

protection to the wires from mechanical injury and may be used for all classes of service. It is chiefly used in buildings of fire-proof construction where wires are concealed; it is also frequently used for circuits run exposed in power houses and industrial establishments. Conduit systems must be *grounded*, that is connected to the earth, by connecting the conduit to a water pipe (on the street side of the meter); grounding is necessary so that in case of a breakdown of the wire insulation, the conduit will not be charged to a dangerous potential.

Flexible Conduit Wires are installed in a flexible conduit that is made of steel strips wound spirally, to form a tube; the edges of the strip interlock in such a manner that the tube can be bent to a small radius. Flexible conduit is generally used in concealed work where rigid conduit could not be used. It is not water-tight and therefore is not as suitable as the rigid conduit where exposed to moisture.

Armored Cable A flexible armor similar to the above flexible conduit is placed directly upon the wire. The wire is rubber insulated and covered with a braid the same as the wire used in metal conduit systems. This armored cable is made with either single, double or triple conductors and is used for the same classes of service as flexible conduit, in fact it is used more frequently than the flexible conduit as it is cheaper and easier to install.

In wiring buildings, wherever the size of wire is reduced a fuse must be inserted, the capacity of which must not exceed the permissible current-carrying capacity of the smaller wire. These fuses are located on porcelain cut-outs within steel junction boxes or on slate or marble panel boards within steel cabinets. Panel boards are designed for plug fuses or for cartridge enclosed fuses, ¶ 242, and are often equipped with knife switches. Panel boards with no live parts exposed, called "dead front" panels, are finding increased favor; such panels generally have snap or push-button switches.

QUESTIONS

1. How does a motor differ from a generator?
2. What is the difference between a shunt and a series motor?
3. A series generator rotates clockwise. What will be the direction of rotation when it is used as a motor?

4. A shunt generator runs in a counter-clockwise direction. How will it run when driven as a motor?

5. What change is necessary in order to run the shunt dynamo in Question 4 as a motor in a clockwise direction?

6. Since the counter E.M.F. of a motor permits less current to flow through it than if it did not exist, and the turning effort of a motor depends on the current through the armature, of what advantage then is the counter E. M. F.?

7. State two methods by which you can prove a motor to possess counter E. M. F.

8. Upon what factors does the counter E. M. F. depend?

9. A shunt motor is called a *constant-speed* motor; how is it possible then for the motor to take current from the line in proportion to the power it develops, since if it always runs at constant speed the counter E. M. F. would be constant, and therefore the current constant.

10. Why is it impossible for the counter E. M. F. of a motor to attain a value equal to the applied E. M. F.?

11. What is meant by the speed regulation of a motor?

12. Explain the function of a starting box.

13. What are some uses of motor-generator sets?

14. What factors determine the mechanical power which can be exerted by a motor?

15. What is meant by motor torque?

16. State the conditions of torque and speed that motors are required to develop in commercial work, and the kind of motor adapted to each case.

17. Explain two methods of speed control of shunt motors. Illustrate.

PROBLEMS

1. A shunt motor having an armature resistance of 2 ohms and a field resistance of 125 ohms is connected to 250-volt mains and develops a counter E. M. F. of 220 volts. What current is taken from the line? *Ans.* 17 amperes.

2. What mechanical power is developed by the motor in Problem 1? *Ans.* 4.4 H. P.

3. If there are 500 watts lost in mechanical friction, hysteresis and eddy currents in the motor in Problem 1, what useful power can the motor develop? *Ans.* 3.7 H. P.

4. What is the efficiency of the motor mentioned in the above problem? *Ans.* 65 %.

5. A small shunt motor runs at 1400 rev. per min. when connected to a 220-volt circuit. When driven as a generator it generates 220 volts P. D. at a speed of 1600 rev. per. min. What is the counter E. M. F. when the machine is used as a motor? *Ans.* 192.5 volts.

6. The resistance of the armature in Problem 5 is 1.45 ohms. What current flows through it when the machine is run as a motor at 1400 rev. per min.? *Ans.* 19 amperes.

7. The field of the motor in Problems 5 and 6 receives 3 amperes. If 300 watts are required for mechanical losses, what is the efficiency? *Ans.* 70%.

8. In making a brake test on a motor, the lever arm used is 3 feet long and the motor runs at 1150 revolutions per minute when exerting a pull of 25 pounds. (*a*) What is the motor torque? (*b*) What H. P is developed? *Ans.* (*a*) 75 lb.-ft. (*b*) 16.4 H. P.

9. The counter E. M. F. of a motor is 230 volts; the current through the armature 25 amperes, its resistance 0.4 ohm. What is the applied E. M. F.? *Ans.* 240 volts.

10. Determine the speed regulation of the shunt motor whose characteristic curves are given in Fig. 384, taking the no-load speed as 890 rev. per min. *Ans.* 5%.

11. What tractive effort must be exerted by the two motors of a 15-ton trolley car in order to accelerate the car on a 1.5 per cent grade at the rate of 1.2 miles per hour per sec. *Ans.* 1275 pounds each.

12. If motors whose characteristic curves are shown in Fig. 385 are used on the car of the preceding problem, (*a*) what current will each motor take during acceleration? (*b*) What is the ultimate speed on the grade? *Ans.* (*a*) 72 amperes. (*b*) 21.5 miles per hour.

13. With 6 volts drop on the line what size wire is required to carry current for a 10-H. P., 220-volt motor located 150 feet from the source of supply? The efficiency of the motor is 85 per cent. *Ans.* No. 7 B. & S.

LESSON XXVII

ALTERNATING CURRENTS

Alternating Currents of Electricity. Instantaneous Values of an Alternating Current. Sine Curves. Frequency. Effective Values of Alternating Currents and E. M. F.'s. Form Factor and Peak Factor. Phase. Polyphase Systems. Power Expended in Alternating-Current Circuits. Harmonics. Questions and Problems.

325. Alternating Currents of Electricity. Most of the subject matter so far presented in this book deals with continuous or direct currents. Such a current always flows in a single direction around the electric circuit and in many cases has a constant strength for definite periods of time. An *alternating current* of electricity is a current which changes its direction of flow at regular intervals of time usually much shorter than one second. During such an interval the strength of the current may vary in any way, but in practice the strength rises and then falls smoothly.

Nearly all of the electricity generated today is in the form of alternating current. It will be remembered that direct-current generators are fundamentally alternating-current machines and are equipped with commutators for sending the current in one direction through the external circuit, ¶¶ 276 to 280. Alternating-current motors are used to a great extent industrially, the principal type being the induction motor, which does not require current supply to its rotating member.

In the distribution and transmission of electrical energy from place to place considerable economy is effected by using high voltages. The influence of changing the voltage on the cost of line material can be observed in a numerical example: Suppose 50,000 watts (50 kw.) of power are to be transmitted with a line drop of 2 per cent. If the weight of copper required when the energy is delivered at 100 volts is assumed as 1000 pounds, then the amounts of copper necessary for other voltages are as follows:

Line Voltage E	Line Current I amperes	Line Drop e volts	Power Loss Ie watts	Line Resistance $R = \frac{e}{I}$ ohms	Copper pounds
100	500	2	1000	0 004	1000
200	250	4	1000	0 016	250
500	100	10	1000	0 100	40
1000	50	20	1000	0 400	10

The figures show that *the weight of copper wire required for conducting a certain amount of energy with the same percentage loss on the line is inversely proportional to the square of the transmitting voltage*.

The attainment of the high voltages necessary to realize the economy in transmission above mentioned is much easier and cheaper with alternating than with direct currents. To change the voltage of a direct-current supply requires two machines coupled together to form a motor-generator, ¶ 375. The maximum voltage which can be obtained satisfactorily from a single direct-current generator is in the neighborhood of 5000 volts, the limitation being imposed by insulation and commutation. Higher continuous voltages are obtained by connecting the generators in series. On the other hand, alternators can be designed for 20,000 volts because the stationary armature may be more readily insulated. Further, transformers may be used to change the alternating voltage over a wide range. The original cost and upkeep of a transformer is much less than of a motor-generator, and its efficiency is considerably higher. It is primarily the transformer, ¶ 357, which has made possible the transmission of large amounts of electric energy over long distances; line voltages of 60,000 to 120,000 volts are not uncommon.

326. Instantaneous Values of an Alternating Current. — It has already been explained that each armature coil of a generator produces an E. M. F. which rises from zero to a certain maximum value and falls to zero again, then reverses in direction, rising to a maximum value and returning to zero, ¶¶ 277, 278. Referring to Fig. 388, suppose that the line OP revolves at a uniform rate about the point O, that is, one end remains fixed at O while the point P moves around the circle in a counter-clock-

wise direction. The angle A between OP and the horizontal line Oa will then be constantly changing. When point P is at a, that is, when the point P is just starting on a revolution, the angle A is zero, because OP lies along Oa. When P reaches f, angle A has become 90°; when it reaches k, 180°; p, 270°; and a again, 360°; or in other words P has reached the starting point

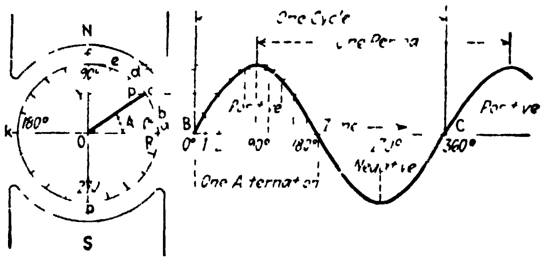


Fig. 388 Plotting a Sine Curve.

again, having made a complete revolution. Now imagine the point P to be an armature coil revolving between the poles **NS.** By following the curve at the right it will be noted that as the coil P moves from a to f the induced E. M. F. gradually rises from zero at B to its maximum value, since the coil when 90° from a is in the position of maximum induced E. M. F.; then moving from f to k the E. M. F. gradually falls to zero; continuing the revolution of the coil it is found (observing the curve) that the E. M. F. gradually rises from zero to its maximum value at 270°, *but in the opposite direction*, since the coil is now under the opposite or S-pole; thereafter the induced E. M. F. again falls to zero as the point P travels from p to a.

The successive instantaneous values of an alternating current may always be represented by a wave-like curve such as shown in Fig. 388. In order to study the effects of an alternating current it is necessary to know the law according to which this curve varies. A consideration of the manner in which the curve has been formed will show that the ordinate of any point P is proportional to the sine of the angle A for that point. Hence it is called a *sinusoid* or a *sine curve*.

The ideal pressure curve from an alternator is sinusoidal.

Commercial alternators, however, do not generate true sinusoidal pressures, but they so closely resemble the curve depicted in Fig. 388 that for most purposes the sine curve can be applied with propriety.

327. Sine Curves. The sine curve of E. M. F. is plotted along the *Time* axis in Fig. 388, as follows: Divide some convenient length along this line, such as BC, into say 20 parts, and also divide the circumference along which P moves into 20 parts. Then the straight line with its subdivisions will represent the distances moved by P around the circle or, what is the same thing, the angles made by the radius with its first position in its revolution around the center O; and these divisions may also be taken to represent the time it takes P to turn through the various values of the angle A. Suppose P to have made $\frac{1}{20}$ of a revolution and to have reached the point b, take a distance along the time base equal to $\frac{1}{20}$ of the length BC, namely from 0 to 1, and at the latter point erect a perpendicular; where this cuts a horizontal line drawn through point b on the circle will give one point on the curve. In the same way for position c, erect a perpendicular at the end of the second space along the time axis, marked 2, and where this perpendicular cuts a horizontal line drawn through c on the circle, there will be another point on the curve. This operation is repeated for different positions of P around its circular path, a series of points being obtained, which, when connected, are found to lie on a wavy line called the *sine curve*.

The wave is known in trigonometry as a *sine wave* for the following reason: Draw the perpendiculars PR and PY to the horizontal and vertical axes respectively. The ratio of PR to OP is known as the sine of the angle A, written sin A. Since OP remains constant while PR increases and decreases as P revolves around the center O, the line PR is always proportional to the sine of the angle A; consequently the perpendicular line, or ordinate, that determines the height of the wave curve at any point is equal to the perpendicular PR corresponding to that point. The wave, therefore, at any point, has a height which is proportional to the sine of the angle that corresponds to that point, hence the name sine wave.

In a similar manner the ratio of PY (or OR) to OP is called

the cosine of angle A, written cos A. A curve of cosines could be drawn with the vertical axis as a center line, and its shape would be identical with the sine wave. Sine and cosine curves are spoken of collectively as *harmonic curves*.

328. Frequency. When, as stated in the foregoing sections, the alternating current or E. M. F. has passed from zero, to its maximum value in one direction, to zero, then to its maximum value in the other direction, and back to zero, the complete set of values passed through during that time is called a *cycle*. This cycle of changes, which is represented by the sine curve depicted in Fig. 388, takes place in a certain time, called a *period* The number of complete periods in one second is called the *frequency* of the pressure or current. A *period* is represented by the time elapsing from one positive maximum to the next positive maximum, although it makes no difference whether one considers a period or cycle to begin when the E M. F. curve is at the horizontal or zero line, or when it has its maximum value, or at any other point; a cycle or period comprises the succession of changes which occur from any one point on the curve to the next point where the curve indicates the same character of E. M. F. or current. The time elapsing from 0° to 360°, Fig. 388, would constitute a period, since a period represents the time of one complete cycle of events.

The term *frequency* is applied to the number of cycles completed in a unit of time one second. It is expressed in *cycles*, meaning *cycles per second*. The word *alternations* was formerly used to express the frequency of an alternator, meaning the number of *alternations per minute*. An alternation is half a period or cycle; in Fig. 388, from 0° to 180° is one alternation. Since the current changes its direction at each half cycle, it follows that the number of alternations or of reversals is twice the number of cycles in a given time.

If the current from an alternator performs the cycle of events depicted in Fig. 388 from B to C sixty times a second, it is said to have a *frequency* of 60 *cycles;* this would mean 120 alternations per second, or $120 \times 60 = 7200$ alternations per minute.

The frequency of an alternating current is always that of the E. M. F. producing it. Frequencies of 25 and 60 cycles are standard in this country.

TO FIND THE FREQUENCY IN CYCLES OF THE PRESSURE OR CURRENT FROM ANY ALTERNATING-CURRENT GENERATOR:

Multiply the number of pairs of poles by the speed of the armature in revolutions per second.

Let f = frequency (cycles per second),
P = number of pairs of poles,
N = speed (revolutions per minute).

Then $$f = P \times \frac{N}{60} \quad \text{. . . . .} \quad (117).$$

Problem 132. What would be the frequency of the current furnished by an alternator having 10 poles and running at 720 revolutions per minute?

By Formula (117) $f = P \times \frac{N}{60} = \frac{10}{2} \times \frac{720}{60} = 5 \times 12 = 60$ cycles.

329. Effective Values of Alternating Currents and E. M. F.'s. – It has been shown that an alternating current is one that is continually changing its value, as well as reversing its direction of flow. It passes through a certain set of values, called a *cycle*, over and over again, the current during each cycle passing through a large range of values from zero to its maximum value. When it is stated that an alternating current of 10 amperes is flowing in a circuit, some average value must be implied, because, as a matter of fact, the current is continually alternating through a wide range of values.

Fig. 389 represents an alternating current having a maximum value of 10 amperes. If this current passes through an ammeter the deflection will be 7.07 amperes, this being the *effective* value of the current. Assuming that this current is furnished by a 60-cycle alternator, the complete set of values represented by the cycle included between A and E is passed over in $\frac{1}{60}$ second. The fluctuations of the current are obviously too rapid for the needle of commercial instruments to follow, and the instrument therefore indicates the mean of the fluctuating values.

The instantaneous values are, as a rule, used very little in calculations. In alternating-current apparatus and circuits, the E. M. F. spoken of is not the maximum E. M. F., but the geometrical average of the E. M. F. values between zero and the

maximum. On the basis of the *sine curve*, this average is 0.707 of the maximum E. M. F. and is termed the *effective* E. M. F. In speaking of alternating voltages, unless otherwise stated the *effective* E. M. F. is always meant, and it is this E. M. F. which is indicated by measuring instruments.

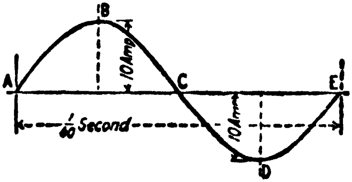


Fig. 389. — Successive Values of a 60-cycle Alternating Current

Maximum value is 10 amperes effective value is 7.07 amperes

To understand the justification of this so-called effective value, consider the current represented by the wave in Fig. 389, having a cycle of values between A and E. Starting at A the current increases from zero to its maximum value at B then decreases to zero again at C; it then passes through a similar set of values in the opposite direction. When the current is at its highest value in either direction it amounts to 10 amperes, but at all other instants it is smaller than this. The question naturally arises: What shall the value of this current be called? The answer is dictated by the *effect* which this current is capable of producing in a circuit.

It has become the universal custom to express alternating currents in terms of the value of the direct current which would produce the same heating effect. For example, suppose 10 amperes of direct current flow through a resistance of 2 ohms. The power dissipated in heat will be $I^2R = 10^2 \times 2 = 200$ watts. Now suppose an alternating current is sent through the same wire and its strength adjusted until the power dissipated in heat is also 200 watts; it is then said that 10 amperes of alternating current flow through the wire. It is readily seen that the heating effect in a wire will increase and decrease as the current increases and decreases, because *at each instant the heating effect will be proportional to the square of the current at that instant.*

Of course, the current varies so rapidly that the heating effect appears to be uniform, but it is clear that the average heating effect must depend upon the heat produced at each instant during the cycle. If the frequency is low enough, the variation in the heating effect under favorable conditions may be noticed

For example, if an incandescent lamp having a thin filament is connected to an alternator that is slowed down to yield a current at about 20 cycles, the light will flicker perceptibly, but if the frequency be raised above 40, the light becomes steady, so far as the eye can judge.

The variation in heating effect of an alternating current is depicted in Fig. 390. Suppose a current, represented by the full-line wave, to reach its maximum value of 5 amperes during each half cycle; also suppose that this current is sent through a resistance of 2 ohms. When the current is at its highest value at B (5 amperes) the rate at which heat is expended will be I^2R or $5^2 \times 2 = 50$ watts. Lay off along BF a distance FG which will represent 50 watts to any convenient scale. Now take another instant during the cycle, as shown at X, and scale off the value of the current XY. Having obtained this value, square it and multiply it by the resistance (2 ohms), and then lay off XZ to the same scale used for FG to represent the watts expended in heating at the instant X. If this is done for a number of points, a curve will be obtained of the shape shown by the dotted line.

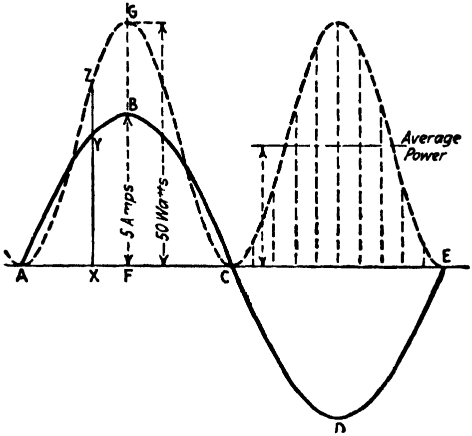


Fig. 390. — Effective Value of an Alternating Current.

Average power is 25 watts

This curve shows that the heating effect varies as the current changes. At first it rises rather slowly from point A, but as the current increases, the heating effect rises rapidly, because it increases with the square of the current. Further, this curve is altogether *above* the horizontal line, since in squaring the negative values of the current the products become positive quantities.

Coming back to the question of what constitutes the value of an alternating current, suppose one lobe of the heating curve in Fig. 390, between C and E, is divided by a number of equally spaced vertical lines, as shown. The average height of these lines is obtained by adding their lengths together and dividing by the number of lines. The sum of these lines represents 250 watts to the same scale, and dividing by 10 lines gives as the average power 25 watts.

The average so obtained gives the *average watts* expended in heat, or the average of all the values of I^2R. Since R remains the same for all, it follows that the average watts divided by the resistance, since $\frac{P}{R} = I^2$, will be the *average of the squares of all the values of the current* at the different instants, and the *square root of the average of these squares* must give the value of the alternating current that will produce the same power or heating effect as a corresponding direct current. This value of an alternating current is sometimes called the *square root of mean square value*, but it is usually called the *effective value*.

In the numerical illustration the average power is 25 watts and the resistance is 2 ohms, therefore the average of the squares of the current values is 25 ÷ 2 = 12.5, and its square root is 3.54 amperes. This is the effective value of the current. In other words, although this alternating current is continually rising and falling between the limits + 5 amperes and − 5 amperes, it only produces the same heating effect in the circuit as would 3.54 amperes of direct current.

The relation between the maximum value of 5 amperes and the effective value of 3.54 amperes is as $\sqrt{2}$ is to 1. Therefore the effective value of a sinusoidal alternating current is equal to the maximum value multiplied by $\frac{1}{\sqrt{2}}$ or 0.707; the maximum value of the current is equal to the effective value multiplied by $\sqrt{2}$ or 1.41.

If an alternating-current ammeter reads 10 amperes, it means that the *effective value* of the current is 10 amperes and that the current actually varies between + 14.1 and − 14.1 amperes. In the same way, if an alternator generates a pressure of 1000

volts as indicated by the switchboard instrument, the effective value is 1000 volts, and the maximum value of the voltage would be $1000 \times 1.41 = 1410$ volts.

Care should be taken not to confuse the *effective value* of the current with the *average value*. By the *effective* value is meant that value which will produce the same heating effect in a circuit as the same value of direct current. By the *average* value is meant simply the average value of all the different values of the current during an alternation, as shown in Fig. 391. If a number of equidistant vertical lines are drawn and their lengths added together and this total divided by the number of lines, there results the average length, representing the average current. Doing this for the sine curve gives $31.8 \div 10 = 3.18$ amperes; if this average value is multiplied by the length AC it would give the area of the rectangle, ADEC, and this area would be equal to the area bounded by the curve ABC and the line AC. The ratio of this average value of 3.18 amperes to the maximum value of 5 amperes is as 2 is to π, or 0.636. Consequently the maximum value is $1 \div 0.636 = 1.57$ times the average value.

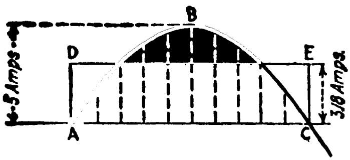


Fig 391 — Average Value of an Alternating Current.

The *average value* of an alternating current is simply the *average of the values* during an alternation, but the *effective value* is the *square root of the average square* of all the different values. For convenience the foregoing relations are here given together

Maximum value $= 1.41 \times$ effective value;
Effective value $= 0.707 \times$ maximum value;
Average value $= 0.636 \times$ maximum value;
Maximum value $= 1.57 \times$ average value.

The effective value, as shown by the above relations, is somewhat greater than the average value. These ratios apply to sine curves of E. M. F. and current only For other shapes of waves the relation might be quite different. A wave with a sharp peak would have a higher maximum value compared with the effective value than given above.

330. Form Factor and Peak Factor.--The ratio of the effective value to the average value of a wave shape is called its *form factor;* a flat wave has a small form factor and a peaked wave a greater form factor. For a rectangular wave shape the form factor is unity. As a curve becomes more peaked, its form factor increases, due to the superior weight of the squares of the longer ordinates. In the sinusoid the values found in the preceding paragraph give

$$\text{Form factor} = \frac{0.707}{0.636} = 1.11.$$

The form factor of a wave shape is significant for certain purposes, as for example in the determination of hysteresis losses in a transformer, in which case the loss becomes greater as the form factor becomes less and vice versa under constant effective supply voltages of different wave shapes. In general, however, form factor has no useful significance as an indication of the shape of a wave or of its departure from a sine wave.

The *peak factor* or *crest factor* is the ratio of the maximum or crest value of a wave to its effective value. For a sine wave its value is 1.41. The peak factor is useful in connection with the testing of insulators and insulating materials.

331. Phase. The term *phase* is used to express the displacement between two alternating currents or two alternating electromotive forces which have the same frequency but which do not rise and fall in unison. It is also applied to the large number of cases where the current in the circuit is not in step with the alternating E. M. F. which is impressed upon that circuit.

The curves of impressed E. M. F. and current in a circuit are frequently plotted together in the same diagram, as illustrated in Fig. 392. The curves have the same horizontal scale of time (or degrees), but have their individual vertical scales of volts and amperes. In some circuits the zero and maximum values of the current curve will occur at the same positions as do the corresponding values of the voltage curve. In such a case, as in Fig. 392 (*a*), the current is said to be *in phase* with the pressure.

In other circuits the current will reach a maximum or a zero value at a time later than the corresponding values of the im-

pressed E. M. F.; this condition is represented in Fig. 392 (*b*). In such a case the current is said to be *out of phase* with, and to *lag* behind the impressed voltage or pressure. In still other circuits the curves are placed as shown at (*c*) and the current and pressure are again *out of phase*, but the current is said to *lead* the pressure. The distance between the zero ordinate of one sine curve and the corresponding zero ordinate of another may

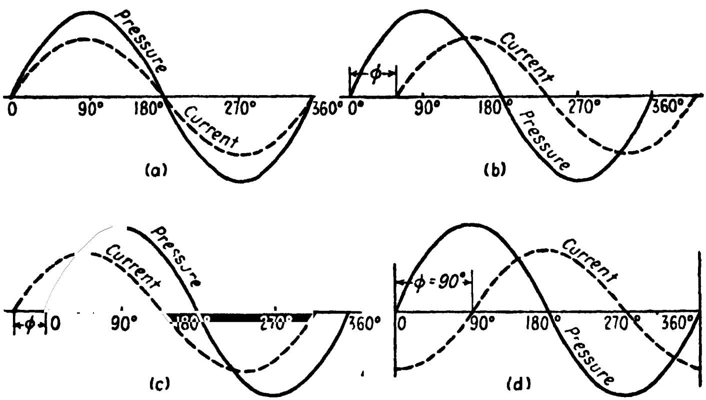


Fig. 392. — Current and Voltage Relations in Alternating-current Circuits.

(*a*) Current in phase with pressure, (*b*) current lags behind impressed voltage, (*c*) current leads the pressure, (*d*) current lags 90 degrees

be measured in degrees and is called the *angular displacement* or *phase difference*. This *angle of lag* or of *lead* is usually represented by ϕ.

When one curve has its zero ordinate coincident with the maximum ordinate of the other, as in Fig. 392 (*d*), there is a displacement of a quarter cycle ($\phi = 90°$). If the zero ordinates of the two curves coincide, but the positive maximum of one coincides with the negative maximum of the other, then $\phi = 180°$, and the curves are in *opposite phase*.

Alternating currents and E. M. F.'s are often represented by lines rather than by sine waves, the lines having definite lengths and definite directions. For example, the situation of a current lagging ϕ degrees behind the impressed electromotive force

shown in Fig. 392(b) is represented by two lines drawn from a common point with an angle ϕ between them, as in Fig. 393 (b). The vertical direction has been chosen for the voltage line, and the lengths of the lines E and I are the same as the maximum values of the alternating voltage and current respectively in Fig. 392. These lines can, of course, be drawn to any convenient scale, and further, they more frequently refer to effective rather than to maximum values. The other diagrams in Fig. 393 show various angles between the voltage and current lines: (c) represents the conditions of Fig. 392 (c), and (d) that of Fig. 392 (d). Such diagrams are termed *vector diagrams*, the individual lines being called *vectors*.

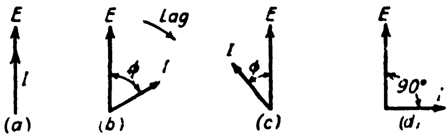


Fig. 393. — Vector Diagrams of Alternating Quantities

With respect to impressed voltage, (a) current is in phase (b) current lags (c) current leads (d) current lags 90 degrees

332. Polyphase Systems. The term *phase* is generally used also when referring to the angular displacement between the E. M. F.'s or currents derived from alternators. An alternator designed to generate a single pressure is called a *single-phase* alternator, a machine designed to generate two separate E. M. F.'s for sending current through two distinct circuits, so that, at the same instant the E. M. F. of one circuit is a maximum while the E. M. F. in the other circuit is zero, is called a *two-phase* generator, ¶ 360. An arrangement of two circuits (four wires) for carrying these currents is termed a *two-phase* or *quarter-phase*

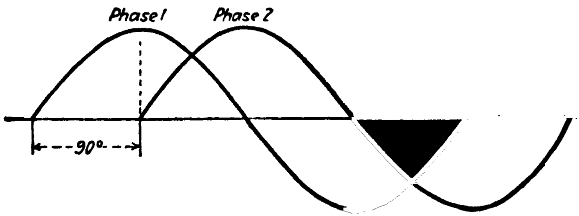


Fig. 394. — Sine E. M. F. Curves of a Two-phase Alternator.

system. The simultaneous pressure curves from the two circuits take the form of Fig. 394, the two E. M. F.'s differing in phase by 90°.

A system of conductors carrying three single-phase currents having an angular displacement of 120°, Fig. 395, is called a *three-phase* system. Such a system requires in practice three

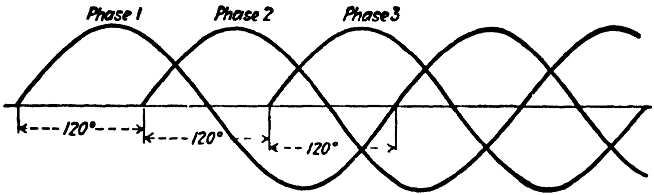


Fig. 395. - Sine E. M. F. Curves of a Three-phase Alternator.

wires, although theoretically, the system consists of three circuits of two wires each; but since the algebraic sum of the currents in the three circuits (if balanced) is at every instant equal to zero, the three return wires, one on each circuit, may be dispensed with, leaving but three wires.

Any arrangement of conductors carrying two or more alternating currents definitely related to one another in time constitute a *polyphase* system. (See ¶ 353).

333. Power Expended in Alternating-Current Circuits. — In direct-current circuits the power expended is the product of the applied E. M. F. and the current. In an alternating-current circuit containing resistance only, the current does not lag with respect to the E. M. F., and the power in watts is also equal to E × I. With inductance or capacitance in the circuit, the current will be out of phase with the impressed E. M. F., the current at times being positive when the E. M. F. is negative; hence the actual power is reduced.

The product of the effective values of current and voltage in an alternating-current circuit is called the *apparent power*. It is expressed in volt-amperes or in kilovolt-amperes. Alternating-current apparatus is usually rated by the apparent power in kilovolt-amperes (abbreviated kv-a.).

When the current in an alternating-current circuit is not in

phase with the impressed E. M. F., the current may be looked upon as made up of two parts or components located at right angles to each other. In Fig. 396 the current vector I lags ϕ degrees behind the E. M. F. vector E; perpendiculars are dropped from P to the horizontal and vertical lines to determine the two components. These components are: OA, at right angles to the impressed E. M. F., is called the *reactive component* of the current, and OB, in phase with the voltage, is called the *active component*. The figure shows that the greater the angle of current lag behind the impressed E. M. F. the greater will be the reactive component and the smaller will be the active component.

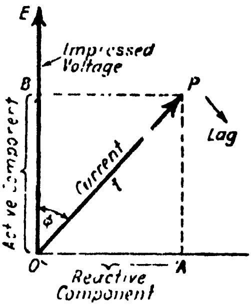


Fig. 396. Active and Reactive Components of an Alternating Current.

The active component is so called because when multiplied by the voltage E it gives the actual power expended in the circuit, that is, the power $P = E \times OB$. Remembering that the ratio of the side OB to the hypotenuse OP of triangle OBP is called the cosine of the angle (¶ 327), the component OB becomes $OP \times \cos\phi = I \times \cos\phi$. Consequently the actual power expended in the circuit is

$$P = E \times I \times \cos\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad (118).$$

The factor $\cos\phi$ is called the *power factor* of the circuit; it is usually expressed in per cent.

TO FIND THE POWER IN AN ALTERNATING-CURRENT CIRCUIT WHEN THE E. M. F. AND CURRENT DIFFER IN PHASE:

Multiply the effective E. M. F. by the effective current and this product by the cosine of the angle of lag or lead.

Since the apparent power is the product of the effective values of voltage and current, it follows that the actual power expended is equal to the apparent power multiplied by the power factor. Also, the *power factor may be defined as the ratio of the actual power to the apparent power*, or

$$\text{Power factor} = \cos\phi = \frac{P}{E \times I} \quad . \quad . \quad . \quad . \quad . \quad (119).$$

In measurements on alternating-current circuits, the product of the readings of a voltmeter and an ammeter will yield the apparent power in the circuit or portion of the circuit to which these instruments are connected. To obtain the actual power from these readings, a knowledge is required of the power factor of the circuit or of the angle of current lag or lead. A wattmeter, however, measures directly the actual power expended. The connections of these instruments to a circuit are given in Fig. 397.

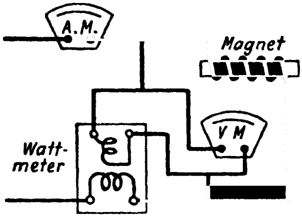


Fig. 397. — Measurement of Power Factor in an Alternating-current Circuit.

Problem 133. — An electromagnet takes a current of 8 amperes when connected to a 110-volt source of alternating current. A wattmeter, connected with its current coil in series with the magnet and its potential coil in parallel with the magnet, is observed to read 615 watts. What is the power factor of the magnet circuit? What is the phase difference between the current and the impressed E. M. F.?

By Formula (119)

$$\text{Power factor} = \frac{615}{110 \times 8} = 0.70 \text{ or } 70 \text{ per cent.}$$

Referring to tables of trigonometric functions, the angle for which the cosine is 0.70 is found to be 45 5 degrees.

The effect of difference in phase on the power consumption may also be shown by the sine waves in Figs. 398 to 400. The first figure shows the current wave in phase with the impressed E. M. F. wave; the power curve is seen to lie wholly above the horizontal axis. The power is positive at all times, since the product of the positive values of E. M. F. and current as well as the products of their negative values are always positive, and its effective value

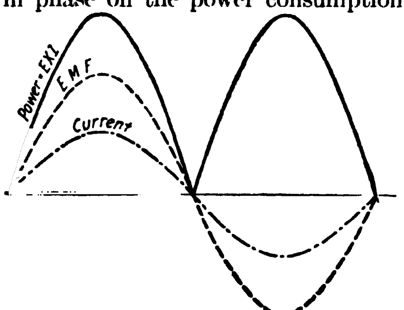


Fig. 398. — Curves of E. M. F., Current and Power in an Alternating-current Circuit Containing only Resistance.

is simply the product of the effective E. M. F. and the effective current, as read on a voltmeter and an ammeter; that is, power = E × I. This represents the condition when the current is flowing through a purely resistive circuit.

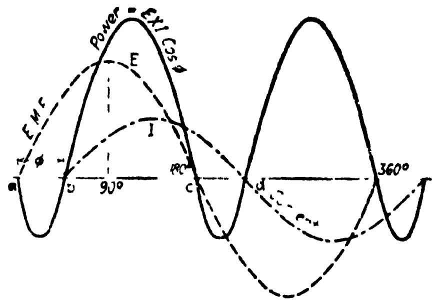


Fig. 399. Curves of E. M. F., Current and Power in a Circuit Containing Inductance

Next suppose that the circuit also contains inductance, the latter causes the current to lag behind the E. M. F. by an angle less than 90°, Fig 399. The power curve is here constructed as before, but it is no longer wholly above the horizontal axis, due to the fact that the current curve at times is positive while the E. M. F. curve is negative; consequently the product of their values at those instants are negative, and the corresponding points on the power curve lie below the horizontal axis. This means that during the intervals of time, ab and cd, negative work is being done; or, in other words, the circuit during those intervals, instead of having work done upon it, is returning energy to the system to which it is connected. In Fig. 400 the angle of lag has been taken as 90° and the power curve lies as much above the horizontal axis as be-

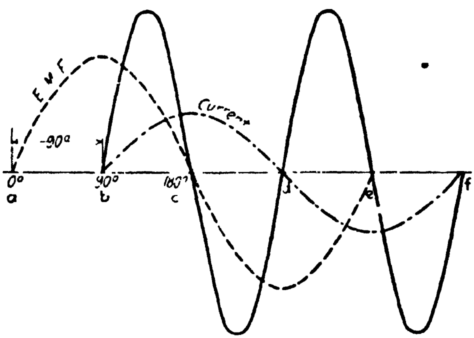


Fig. 400 – Curves of E. M. F., Current and Power in an Inductive Circuit Containing Negligible Resistance.

The current lags 90° behind the impressed E. M. F.

low it, the circuit returning as much energy as is expended in it; the negative power from c to d being equal to the positive power from b to c. The total work done in this case, therefore, is zero, and although a current is flowing, this current does not represent energy expended.

Although reactive currents do not represent any power wasted, they are objectionable, as they merely load up the generator and lines, thus limiting their output as to current-carrying capacity. For example, an alternator furnishing current to a system having a very low power factor may be delivering a small amount of power, so that little power would be required to drive the alternator. At the same time the current is circulating through the lines and the armature of the alternator, thus heating the line wires and heating the machine also. As the current output of the armature is limited to a great extent by this heating, it is seen that the useful current which may be taken from the alternator is cut down by the presence of this reactive current. In practice, alternating-current apparatus is always designed so as to have as high a power factor as possible consistent with other requirements.

334. Harmonics. - If several electromotvie forces are impressed upon a circuit at the same time, the effect is the same as

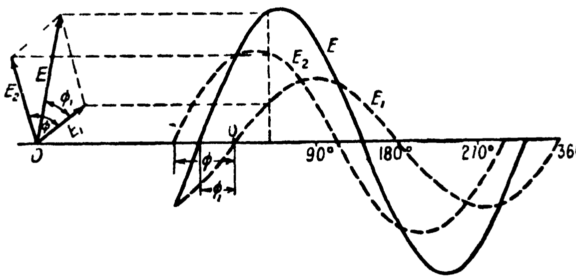


Fig. 401. — Addition of Voltages Having the Same Frequency.

that produced by a single E. M. F. which has at each instant a voltage equal to the sum of the various components at that instant. For two sinusoidal voltages E_1 and E_2 having the same frequency and the same phase, the resultant is evidently a sine

wave equal to their sum; that is, the maximum value of the resultant E is equal to the sum of the maximum values of E_1 and E_2. Since with a sine wave the effective value is 0.707 times the maximum value, it follows that the effective value of the resultant voltage is equal to the sum of the effective values of E_1 and E_2.

The more general case of the addition of two alternating voltages, involves E. M. F.'s of the same frequency, but of different magnitude and phase. In Fig. 401 are shown two sine waves

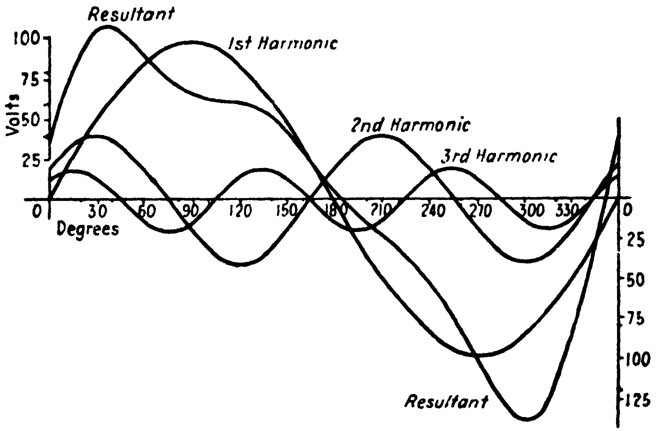


Fig. 402. — Addition of Three Voltages Having Related Frequencies.

representing voltages E_1 and E_2, the angle between them being ϕ. Adding the ordinates of these curves at each point along the horizontal time (or degree) axis results in the sinusoidal wave E. It is quite clear from the figure that the maximum value of E is *not* equal to the sum of the maximum values of E_1 and E_2, but is less than this sum.

The vector diagram at the left of the figure shows how the maximum value of the resultant of the two voltages may be ascertained more readily. Lines E_1 and E_2 represent to the same scale the maximum values of the voltages and they are drawn from a common point O with an angle ϕ between them. A parallelogram is constructed upon these lines as sides, and the

diagonal is then drawn from O. The length of this diagonal represents to the same scale the maximum value of the resultant voltage. The position of the diagonal is ϕ_1 degrees ahead of E_1, therefore the resultant leads voltage E_1 by an angle of ϕ_1 degrees.

Alternating E. M. F.'s of different frequencies applied to the same circuit will give, in general, an irregular wave form. In practice, the frequencies of some E. M. F.'s are multiples of the frequency of another, called the *fundamental* E. M. F., or *first harmonic*. The pressure curve having twice this frequency is termed the *second harmonic;* another having three times this frequency, the *third harmonic*, and so on. The resultant instantaneous E. M. F. is obtained by adding the pressure values of all the components at that instant.

When both odd and even harmonics are present, the resulting curve will have unlike lobes, but when only odd harmonics occur. as is usual in electrical machinery, the lobe above the horizontal axis and the other below it will be similar. Fig. 402 shows the resulting E. M. F. of three sinusoidal components having the following maximum values: 1st harmonic 100 volts, 2nd harmonic 40 volts, and the 3rd harmonic 20 volts; the latter two lead the first by 15 degrees on the scale of the first harmonic.

It is possible by graphical and analytical methods to determine the harmonics which are present in complicated wave shapes obtained by experiment.

QUESTIONS

1. How does an alternating current differ from a continuous or direct current?
2. What advantage has the alternating current over the direct current?
3. What do you understand by the term frequency?
4. How would you determine the frequency of any alternator?
5. Draw with accuracy a sine wave having a length of 4 inches and a maximum ordinate of 1.5 inches.
6. What is meant by the effective value of an alternating current?
7. What are the relations between the average, effective and maximum values of an alternating current?
8. Give definitions of form factor and peak factor.
9. What is meant by phase angle?
10. Construct a vector diagram to indicate the voltage phase relations of a three-phase system.

11. Will the product of volts by amperes give the true power expended in an alternating-current circuit? Why?

12. What is meant by power factor? How is it measured?

13. Prove that the actual power expended in a circuit is equal to the volt-amperes multiplied by the power factor.

14. Why do you believe that alternating-current apparatus should be rated in kv-a. rather than in kw.

15. What is a third harmonic wave?

16. Sketch the shape of the resultant wave of a fundamental sine curve with a symmetrically-located third harmonic.

PROBLEMS

1. An ammeter in a certain circuit indicates 15 amperes. What would be the maximum value of this alternating current? *Ans.* 21.15 amperes.

2. An alternator has 24 poles and its armature rotates at a speed of 300 revolutions per minute. (*a*) What will be the frequency of its voltage? (*b*) How many times would the current change its direction in one minute? *Ans.* (*a*) 60 cycles; (*b*) 7200.

3. What must be the speed of a 12-pole alternator to yield an E. M. F. of 60 cycles? *Ans.* 600 rev. per min.

4. What is the phase displacement between sinusoidal waves respectively of 100 volts and 10 amperes maximum value, when the power expended in the circuit is 424 watts? *Ans.* 32 degrees.

5. Two 60-cycle alternators coupled to the same motor shaft generate 80 volts and 60 volts with a constant phase difference of 90 degrees. What single alternating voltage would produce the same effect in a circuit as the two from the alternators when simultaneously impressed upon that circuit? *Ans.* 100 volts.

6. What current will a 240-volt alternator produce in a circuit which has a power factor of 90 per cent and takes 1 kilowatt? *Ans.* 4.63 amperes.

LESSON XXVIII

ALTERNATING-CURRENT CIRCUITS

Properties of an Electric Circuit — Inductance — Inductive Reactance — Components of Impressed E. M. F. — Impedance — Graphical Illustrations of Impedance, Reactance and Resistance — Reactors — Capacitance — Capacitive Reactance — Current and Voltage Relations in Condensive Circuits — Impedance of a Condensive Circuit — Angle of Lag or Lead — Condensers Connected in Parallel and in Series — Condensers — Circuits having Inductance, Capacitance and Resistance — Ohm's Law for Alternating-Current Circuits — Impedances in Series — Impedances in Parallel — Polyphase Circuits Power in Polyphase Systems — Resonance — Table XXI — Electric Filters — Questions and Problems.

335. Properties of an Electric Circuit. – The flow of a direct current for a given impressed E. M. F. is entirely determined by the resistance of the various parts of the circuit. The flow of an alternating current depends not only upon the resistance, but also upon any *inductance* (self or mutual) or *capacitance* that may be contained in or connected with the circuit. These two properties, inductance and capacitance, have no effect upon a direct current after a steady state has been established, which condition is usually reached in a fraction of a second. In an alternating-current circuit either or both of them may be far more important than the resistance and in some cases may entirely control the current flow.

The difference in the effects of inductance and capacitance in direct- and alternating-current circuits is due entirely to the fact that the alternating current is constantly changing its value and periodically changing its direction. In consequence the magnetic field (associated with inductance) and the electrostatic field (associated with capacitance) must be established first in one direction, then in the opposite direction, etc., many times per second. The result of such rapidly changing magnetic and electrostatic fields will be considered in this lesson.

Resistance in an alternating-current circuit has exactly the

same effect as it has in a direct-current circuit. This property of an electric circuit always occasions a loss which appears as heat. If an alternating current of I amperes (effective value) flows through a resistance of R ohms, the loss will be I^2R watts.

If an alternating current is passed through a circuit containing only resistance, the current strength will be the impressed E. M. F. divided by the resistance, as dictated by Ohm's Law, effective values of both current and E. M. F. being used. In such a circuit the current wave will be in phase with the wave of applied voltage, as shown in Fig. 392 (a).

336. Inductance. It has been shown in previous lessons that when a current flows through a wire a magnetic field is set up around the wire; in consequence, with an alternating current passing through the wire the magnetic field will change continually. Whenever the magnetic field surrounding a wire is made to charge, an E. M. F. is set up in the wire, and this induced E. M. F. opposes the current. For example, when the current rises in the positive direction, the lines of force increase in, say, the clockwise direction about the conductor; after the current reaches the maximum value and begins to decrease, the lines of force commence to collapse, reaching zero value when the current becomes zero; then when the current rises in the negative direction the magnetic lines expand in the counter-clockwise direction and so on. The result is that the counter E. M. F. of self-induction, instead of being momentary (as it is when a direct current is established or interrupted) is continuous, but varies in value like the applied E. M. F. or the current.

The value of an induced E. M. F. is proportional to the rapidity with which lines of force are cut by the conductor, and as the lines of force vary most rapidly when the curve of current or magnetic flux passes the zero point (changing from + to − or *vice versa*), the induced E. M. F. is a maximum at that moment. When the current, and therefore the magnetism, has the maximum value in either direction, its strength varies very little within a given momentary period of time, and consequently the *induced* E. M. F. is zero at that moment. Therefore the E. M. F. of self-induction does not rise and fall in unison with the applied E. M. F. and the current, but lags behind the current exactly a quarter of a cycle, as shown in Fig. 403.

This property of a wire or coil to act upon itself *inductively* (self-induction) or of one circuit to act inductively on another independent circuit (mutual induction) is termed *inductance,* the symbol for which is L. The unit or *coefficient* of inductance is called the *henry,* ¶ 268, and is the inductance of a circuit in which the induced E. M. F. is one volt when the *current varies at the rate of one ampere in one second.*

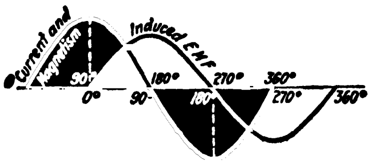


Fig. 403. — E. M. F. of Self-induction Lagging a Quarter of a Cycle behind the Current.

The amount of inductance possessed by a circuit depends upon the amount of magnetic flux associated with it. Most electrical devices have inductance; a coil of wire may have a high inductance, a lamp filament has very little.

337. Inductive Reactance. – It has been learned that the effect of *inductance* in an alternating-current circuit is to oppose the flow of current because of the counter E. M. F. which is set up. This opposition may be considered as an apparent additional resistance, and is called *inductive reactance* to distinguish it from ohmic resistance.

Reactance is expressed in ohms, like resistance, because it constitutes an opposition to the flow of the current. Unlike resistance, however, this opposition does not entail any loss of energy because it is due to a counter pressure and is not a property analogous to friction. Its effect in practice is to make it necessary to apply a higher E. M. F. to a circuit in order to pass a given current through it than would be required if only resistance were present. The value of the inductive reactance in ohms depends upon both the inductance of the circuit and the frequency of the voltage; it may be expressed by the formula

$$X_l = 2\pi \times f \times L, \quad \ldots \ldots \ldots \quad (120).$$

where L = inductance (henrys),
f = frequency (cycles per second),
π = ratio of the circumference of a circle to its diameter = 3.1416.

Transposing Formula (120) there results

$$\text{inductance} = \frac{\text{inductive reactance}}{2\pi \times \text{cycles}},$$

or

$$L = \frac{X_l}{2\pi \times f} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (121).$$

Problem 134. — What would be the inductive reactance of a coil of wire having an inductance of 0.02 henry when connected to an E. M. F. of 60 cycles?

By Formula (120) $X_l = 2\pi \times f \times L = 6.28 \times 60 \times 0.02 = 7.536$ ohms.

Problem 135. What would be the inductance of a coil which has an inductive reactance of 8 ohms when connected to an E. M. F. of 120 cycles?

By Formula (121) $L = \frac{X_l}{2\pi \times f} = \frac{8}{6.28 \times 120} = \frac{8}{753.6} = 0.0106$ henry.

To derive Formula (120), consider a sinusoidal current of frequency f to have a maximum value of I amperes. The current will then vary from + I to − I amperes in a half period, that is in ½ of $\frac{1}{f}$ or in $\frac{1}{2f}$ second. The *average* rate of change over this current range of 2I amperes is therefore $2I \div \frac{1}{2f} = 4fI$ amperes per second. Remembering that a circuit having an inductance of one henry will set up an E. M. F. of self-induction of one volt when the current therein changes at the rate of one ampere per second, it follows that the induced E. M. F. in a circuit of L henrys, in which the current changes by an average of 4fI amperes in one second, will have the *average* value of 4fLI volts. The corresponding maximum voltage value is obtained by multiplying the foregoing expression by 1.57 or $\frac{\pi}{2}$, as explained in ¶ 329; thus both voltage and current will be expressed in terms of maximum values. The induced voltage is therefore

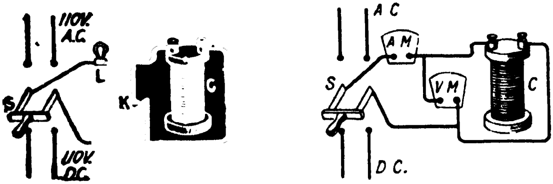
$$E_l = 2\pi fLI.$$

Since both E_l and I are sinusoidal, the formula applies also to *effective values* of voltage and current, since dividing both sides of the equation by $\sqrt{2}$ leaves the result unchanged. Finally, dividing through by the current, gives as the inductive reactance

$$X_l = \frac{E_l}{I} = 2\pi fL.$$

The effect of inductance in an alternating-current circuit can be illustrated by Experiments 106 and 107.

Experiment 106. — In Fig. 404 (a) the solenoid C, of several ohms resistance and wound in the ordinary manner, is connected in series with an incandescent lamp L to a source of direct current (D.C.) by throwing the switch S down. The brilliancy of the lamp is practically the same with the solenoid in circuit as when it is cut out by depressing key K. Neither is there any change in the brilliancy of the lamp when an iron core is inserted in the coil. The circuit is then connected to a source of alternating current (A.C.) by throwing S up. With the solenoid out of circuit the lamp is illuminated as brilliantly as before, but when it is inserted by opening key K the lamp burns dimly. The current through it has been decreased by the



(a) (b)

Fig. 404. — Effect of Inductance.

inductance of the solenoid. If an iron core is now gradually inserted in the coil, the current will be reduced and the lamp may cease to be illuminated. The E. M. F. of self-induction chokes back the current, so that less current is taken from the line. A device for regulating the current in an alternating-current circuit is based on this principle, and is called a *choke coil*, ¶ 341. The flow of alternating currents can thus be regulated much more economically than that of direct currents, since in the latter case regulation is effected by absorbing the energy in resistance.

Experiment 107. — In Fig. 404 (b) the solenoid C is first connected to a source of direct current, and the voltage is raised in order to obtain some definite current strength. The pressure required to cause the known current to flow through the coil is, say, 30 volts. The coil is then subjected to an alternating pressure of such a value that the current through it, as indicated by the ammeter, is the same as before; the potential difference across it is now found to be 100 volts. An alternating pressure of 100 volts is, therefore, required to send the same current through the coil as was maintained by 30 volts from the direct-current source.

338. Components of Impressed E. M. F. — The circuits met with in practice always have resistance as well as inductance. In consequence the voltage impressed upon such a circuit may be viewed as made up of two components; one, required to

overcome the resistance, and the other, required to neutralize the counter E. M. F. of self-induction.

The first component is determined from Ohm's Law to be $E_r = RI$. It will be remembered that the current in a circuit having only resistance will be in phase with the impressed voltage, ¶ 335; consequently in an inductive circuit, that component of the impressed voltage which is necessary to overcome resistance must be in phase with the current. This condition is shown in the vector diagram of Fig. 405 by drawing the line ab to represent E_r along the horizontal axis designated as the *phase of current*.

The other component of the impressed voltage, necessary to neutralize the counter E. M. F. of self-induction, will be equal to and in direct opposition to that counter E. M. F. The value of the latter has been determined in the preceding section as $E_l = 2\pi fLI$, and its phase has been ascertained in ¶ 336 as lagging 90° behind the current. Consequently the component of the impressed E. M. F. is located opposite to, or 180° away from, the counter E. M. F. of self-induction, that is 90° ahead of the current phase; it is shown as line bc in Fig. 405 drawn at right angles to ab.

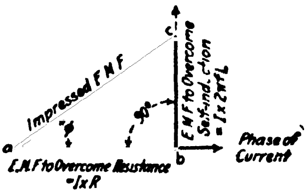


Fig. 405. - Components of E. M. F. Impressed on Inductive Circuit.

Both components of the impressed voltage have been located in the figure, and their resultant will be the diagonal line ac. Now since abc is a right-angled triangle, it follows that the length ac = $\sqrt{\overline{ab}^2 + \overline{bc}^2}$, because the square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides.

Remembering that:

$ab = E_r = RI$ = resistance drop,
$bc = E_l = 2\pi fLI$ = reactance drop,
$ac = E$ = impressed E. M. F.;

it follows that the impressed E. M. F. becomes

$$E = \sqrt{E_r^2 + E_l^2}, \quad \ldots\ldots\ldots\ldots \quad (122.)$$

or $$E = \sqrt{(I \times R)^2 + (I \times 2\pi fL)^2}. \quad . \quad . \quad . \quad . \quad (123).$$

The equations show that the voltage drop due to resistance and that due to inductance cannot be added arithmetically to obtain the total voltage on the circuit, but must be added geometrically at right angles to each other.

Experiment 108. — Connect an incandescent lamp, L, Fig. 406, in series with a coil, M, which has a considerable amount of inductance. Connect the two across a 110-volt alternating-current circuit. Measure the voltage across the lamp, E_1, and that across the coil, E_2, add these two voltages, and the result will be that the arithmetical sum is greater than the line voltage E. This is always so in an inductive circuit because of the difference of phase between the component voltages. If, now, these two devices are connected across a direct-current circuit and the drop across the lamp is added to that across the coil the sum of the two would, of course, be equal to the line voltage of 110 volts.

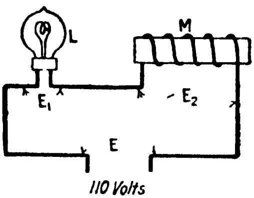


Fig. 406. — Effect of Inductance in an Alternating-current Circuit.

Problem 136. — In Experiment 108, Fig. 406, suppose the drop on the lamp is 46 volts and the drop on the inductance coil (resistance neglected) is 100 volts; what would be the applied E. M. F.?

By Formula (122)

$$E = \sqrt{E_r^2 + E_l^2} = \sqrt{46^2 + 100^2} = \sqrt{12116} = 110.7 \text{ volts}.$$

From the relations shown in Fig. 405 the following definitions may be given for resistance and reactance in an alternating-current circuit:

RESISTANCE is that quantity which when multiplied by the current gives that component of the impressed E. M. F. which is in phase with the current.

REACTANCE is that quantity which when multiplied by the current gives that component of the impressed E. M. F. which is at right angles to the current.

339. Impedance. — The combined effect of resistance and reactance is called *impedance*, to distinguish it from its two components. It is the impedance of a circuit which when multiplied by the current flowing through it gives the impressed E. M. F. The impedance is also expressed in ohms; its symbol is Z.

Factoring out the current I in Formula (123), the impressed voltage on an inductive circuit becomes

$$E = I\sqrt{R^2 + (2\pi f L)^2}, \quad . . . . . \quad \textbf{(124)}.$$

or

$$E = I\sqrt{R^2 + X_l^2}. \quad . . . . . . \quad \textbf{(125)}.$$

Consequently, the impedance (in ohms) of any circuit may be expressed by the following formulæ:

$$\text{Impedance} = \sqrt{\text{resistance}^2 + \text{reactance}^2},$$

or

$$Z = \sqrt{R^2 + (2\pi f L)^2}, \quad . . . . . \quad \textbf{(126)}.$$

or

$$Z = \sqrt{R^2 + X_l^2} \quad . . . . . . \quad \textbf{(127)}.$$

Problem 137. — What would be the impedance of a coil of 4 ohms resistance and 8 ohms reactance?

By Formula (127) $Z = \sqrt{R^2 + X_l^2} = \sqrt{4^2 + 8^2} = \sqrt{16 + 64} = 8.94$ ohms.

GIVEN THE IMPEDANCE AND RESISTANCE, TO FIND THE REACTANCE, USE:

$$X_l = \sqrt{Z^2 - R^2}.$$

GIVEN THE IMPEDANCE AND REACTANCE, TO FIND RESISTANCE, USE:

$$R = \sqrt{Z^2 - X_l^2}.$$

340. Graphical Illustrations of Impedance, Reactance and Resistance. – The relations expressed by Formula (127) may be represented by a right-angled triangle, ABC, Fig. 407 (a). The ohmic resistance R is laid off on a convenient scale to form the base line, the reactance X_l or $2\pi f L$ is laid off also in ohms to form the perpendicular, and the impedance in ohms is found by measuring the hypotenuse of the triangle. Such a triangle is frequently used to represent the relations between resistance, reactance and impedance and also for convenience in obtaining other quantities.

When the reactance is small compared with the resistance, it has very little effect. This is shown in Fig. 407 (b). The line BC is short compared with AB and the impedance represented by AC is not much larger than the resistance AB. When the reactance is doubled, or BC′ = 2 × BC, the impedance AC′ is not much increased over its former value AC. When the

reactance is large compared with the resistance, the impedance is much greater than the resistance, and the angle between them is large. This is shown in Fig. 407 (c).

In coils where the inductance is large compared with the resistance, the resistance may often be entirely neglected, so that it is sufficiently correct to say that the current equals the E. M. F. divided by the reactance. If the frequency is doubled in such cases, the reactance is doubled and the current at the same potential is reduced one-half.

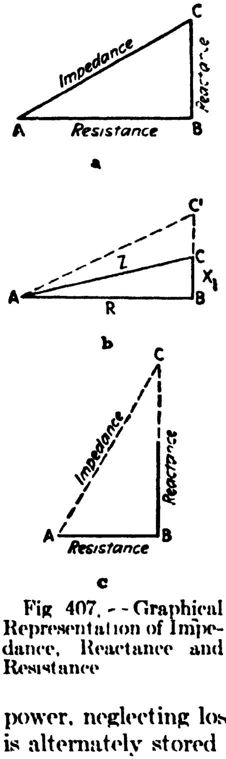


Fig 407.--Graphical Representation of Impedance, Reactance and Resistance

341. Reactors. – A coil or winding which utilizes the counter E. M. F. of self-induction for the operation, control or protection of electric circuits is called a *reactor*, or a *reactance coil*, or a *choke coil*. Such a coil possesses much inductance and relatively little resistance. Reactors with iron cores are often used on alternating-current circuits in such places as resistors or rheostats are used on direct-current circuits, that is, for reducing the line voltage to an amount appropriate for the device being operated. The voltage drop in a reactor of negligible resistance which carries a current I amperes of frequency f, is $2\pi fLI$, where L is the inductance of the reactor, assumed constant. This drop is effected without loss of power, neglecting losses in hysteresis and resistance, for energy is alternately stored in the magnetic field of the reactor and returned to the electric circuit; the device is, therefore, more economical than a resistor which would perform the same function.

It is often desirable to adjust the inductance of reactors, and for this purpose several simple arrangements may be utilized. The coil may have a sliding iron core, or its winding may have several taps. Reactors having U-shaped magnetic circuits are sometimes provided with movable pole-pieces, which serve to

change the length of the air gap, and thereby to alter the inductance.

Reactors without iron cores are used with lightning arrester equipments and for limiting the current in circuits and machines under short-circuit conditions. Since a lightning discharge is oscillatory in character and of enormous frequency, a coil which would offer a negligible impedance to an alternating current of commercial frequencies will offer a high impedance to a lightning discharge. A choke coil of but few turns will offer so great an impedance to a lightning discharge that this high-frequency current will find an easier path to the ground through an air gap suitably provided than through the machinery, and the latter is thus protected.

Reactors for limiting current under short circuits are subjected to high transient voltages and currents, and must be carefully designed so that there is no tendency to deformation from forces set up by the mutual attraction and repulsion between turns when traversed by short-circuit currents. These reactors are formed of circular and helical coils supported in porcelain cleats or cast in concrete. Where several reactors of the same polyphase circuit are located close together, they must be installed rigidly to prevent any movement during short circuit.

342. Capacitance. – When two conductors or conducting plates are placed close together with a non-conducting medium between them, an electrostatic field will be established around these plates when a difference of potential is maintained between them. Such an arrangement is called a *condenser.* The construction of a condenser for use with an induction coil was described in ¶ 271; it consists of many sheets of tin foil interleaved with sheets of waxed paper, alternate tin-foil sheets being connected to each of the two terminals. A condenser possesses *electrostatic capacity*, or simply *capacitance;* that is, it has the property of storing energy in an electrostatic field. Capacitance, like inductance, plays an important part in alternating-current circuits.

The capacitance of a condenser is measured in terms of the *farad* as a unit. The farad is the capacitance of a condenser which will be charged to one coulomb of electricity when its plates have a difference of potential of one volt. When two

volts are impressed on this condenser, it will be charged to 2 coulombs. When two volts are impressed on a larger condenser having a capacitance of 3 farads, the charge on it will be $2 \times 3 = 6$ coulombs. In general, if E volts are applied to a condenser of C farads capacitance, the charge in coulombs will be

$$Q = E \times C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \textbf{(128)}.$$

$$\text{Coulombs} = \text{volts} \times \text{farads}.$$

If a galvanometer is connected in series with a condenser and a continuous E. M. F. is applied to the circuit, a current will flow for only a brief interval. Again, if the terminals of the circuit are disconnected from the source of current and connected together, the galvanometer will be deflected momentarily in the reverse direction. There is a momentary current just at the instant the condenser is *charged*, and a reverse momentary current when it is *discharged*.

If a condenser is connected to a source of alternating current and a galvanometer is joined in the circuit, it will be found that the galvanometer indicates a current flow as long as the alternating E. M. F. is applied to the circuit. The circuit acts just as if it were complete, thereby exhibiting the peculiar condition of a current apparently flowing through a circuit which has a complete break in it, for it will be remembered that there is no connection between adjacent plates of the condenser.

What actually occurs is this: the condenser is charged to a potential equal to the maximum applied E. M. F. during the first quarter of a cycle, is discharged during the second quarter, is charged again, but in the opposite direction, during the third quarter of the cycle, and is discharged during the fourth quarter, this process continuing as long as the condenser remains in circuit and the alternating pressure is applied. The condenser is thus charged and discharged continually, so that current will flow in the circuit in spite of the fact that the two sides of the condenser are insulated from each other.

Most circuits possess to a greater or less degree the same property as a condenser, namely that of holding a certain charge of electricity, and this has a marked influence upon the behavior of an alternating current flowing in the circuit. The capacitance of most circuits met with in practice is quite small in comparison with their inductance and resistance, consequently

its effect is not usually so noticeable; however in some cases, especially in underground and submarine cables and in long overhead lines, these effects become important. Ordinary electrical devices, such as lamps, motors and coils, have little capacitance.

The farad is much too large a unit for the capacitances met with in ordinary practice; the commercial unit is the *microfarad*, which is one-millionth part of a farad. In radio communication still smaller units are commonly used; for example, the *milli-microfarad*, which is one-billionth of a farad.

343. Capacitive Reactance. It was pointed out in the last section that a condenser in an alternating-current circuit is equivalent to a closed circuit so far as maintenance of current flow is concerned. The condenser, however, does present some opposition to current flow, and this opposition can be considered (like that offered by inductance) as an apparent resistance. It is found that the current flow increases directly with the increase of capacitance, and also with the increase of frequency, therefore this apparent resistance due to the condenser, called *capacitive reactance*, is inversely proportional to these quantities. Calling C the capacitance in farads, and f the frequency, the capacitive reactance will be

$$X_c = \frac{1}{2\pi f \times C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (129).$$

Problem 138. — What would be the capacitive reactance of a 25-microfarad condenser to an alternating current of 60 cycles?

Since 25 microfarads = 0.000025 farad, by Formula (129)

$$X_c = \frac{1}{2\pi f \times C} = \frac{1}{2 \times 3.1416 \times 60 \times 0.000025} = \frac{1}{0.0094} = 106.38 \text{ ohms}.$$

Experiment 109. — If a condenser, C, is placed in series with a lamp, L, Fig. 408, and the two terminals, T_1 and T_2, are connected to a supply of direct current, no steady current will flow unless the insulation of the condenser breaks down. It will be noticed that just after the pressure is applied a pulse of current will flow for a short interval and cause the lamp to flash; also if the terminals, T_1 and T_2, are disconnected from the source of the current and connected together, the lamp will flash again. This demonstrates that there is a momentary current at the instant the condenser is charged and another when it is discharged. If an alternating pressure of 110 volts is applied to the terminals, the lamp will be steadily illuminated, for when the current flows in one direction the condenser is charged,

and when the current reverses the condenser is discharged through the lamp, the action taking place so rapidly that the lamp is illuminated as if connected directly to the alternating-current source.

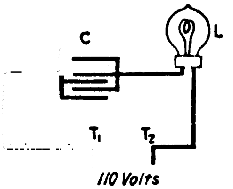


Fig 408. — Capacitance in an Alternating-current Circuit.

Experiment 110. — Fig. 409 shows an arrangement that illustrates a peculiar effect of inductance and capacitance combined. Here L_1, L_2 and L_3 are incandescent lamps of the same kind, M is an adjustable inductance made up of a coil that can be moved over an iron core, and C is a condenser. If the entire circuit is connected to direct-current service mains of, say, 110 volts, no current at all would flow through the lower branch on account of the condenser. If, however, alternating current is applied, current will flow through each branch. The striking point is that if M is adjusted to the proper amount, lamp L_1 can be made to operate at a dull red while lamps L_2 and L_3 are illuminated to full brightness. In other words, the sum of the two currents through L_2 and L_3 is less than either current. Such a result would, of course, be impossible with direct currents.

The alternating current in lamp L_1 is the resultant of the currents in the two branches. The current in the inductive circuit will lag nearly

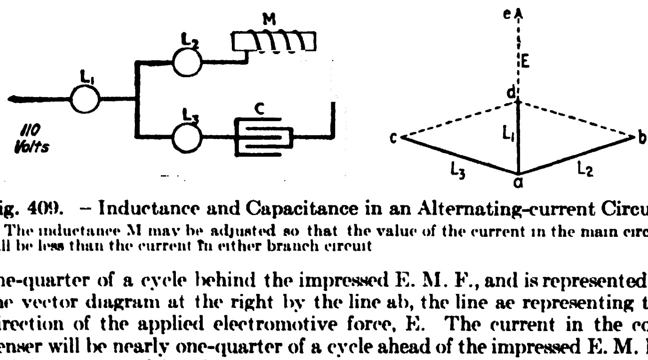


Fig. 409. – Inductance and Capacitance in an Alternating-current Circuit.
The inductance M may be adjusted so that the value of the current in the main circuit will be less than the current in either branch circuit

one-quarter of a cycle behind the impressed E. M. F., and is represented in the vector diagram at the right by the line ab, the line ae representing the direction of the applied electromotive force, E. The current in the condenser will be nearly one-quarter of a cycle ahead of the impressed E. M. F., and is represented by the line ac. The inductance is assumed to be adjusted so that ac = ab. The current in lamp L_1 is the vector sum of ab and ac, and is represented by the length of the line ad. It is seen that, because of the phase relation of ac and ab, this current may be much smaller than either of the currents in L_2 or L_3 taken by themselves.

To derive Formula (129), consider a sinusoidal voltage wave of frequency f to be impressed upon a condenser of capacitance C farads. If the maximum value of the voltage is E, the charge

on the condenser will have a maximum value of CE coulombs, by Formula (128). This means that in a half cycle the charge will vary from + CE to − CE, a change of 2CE coulombs. Since this change occurs in ½ of $\frac{1}{f}$ or in $\frac{1}{2f}$ second, the *average* current will be the quantity of electricity divided by the time, ¶ 93, or $2CE \div \frac{1}{2f} = 4CEf$ coulombs per second (or amperes). The corresponding maximum current value is obtained by multiplying the foregoing expression by 1.57 or $\frac{\pi}{2}$, as explained in ¶ 329. Therefore the maximum value of the current will be

$$I = \frac{\pi}{2} \times 4CEf = 2\pi CEf.$$

Since both I and E are expressed by maximum values, and since both are equally related to their effective values, namely by the ratio $\sqrt{2}$ to 1, the foregoing equation also applies to *effective values* of both I and E. Consequently, calling the voltage E_c,

$$E_c = \frac{1}{2\pi fC} \times I.$$

Finally, dividing through by the current, gives as the capacitive reactance

$$X_c = \frac{E_c}{I} = \frac{1}{2\pi fC}.$$

344. Current and Voltage Relations in Condensive Circuits. — In order to ascertain the phase relations between the voltage and current in a condensive circuit, such a circuit will be compared with a pipe line through which water is made to flow, first one way, then the other, by a piston oscillated pump-like in one section of it. The pipe circuit corresponds to an electric circuit, the pump to a generator of alternating E. M. F., and the flow of water to a flow of alternating current. Imagine one section of the pipe to be enlarged, and in it placed a transverse elastic diaphragm; this pipe section serves as a good analog to a condenser, Fig. 410.

Picture the diaphragm in its medial position, with equal volumes of water on both sides of it, and the piston in the middle of its travel. This middle point corresponds to zero pressure.

When the piston is completely depressed there is a maximum negative pressure, when completely elevated, a maximum positive pressure, if pressure and flow upward are considered positive. If the piston oscillates in its path with a regular motion, it is clear that the water will flow upward from the extreme lowest to the extreme highest position of the piston. That is, there will be flow in the positive direction from the maximum negative to the maximum positive values of pressure. The direction of flow is seen to remain unchanged while the piston passes through

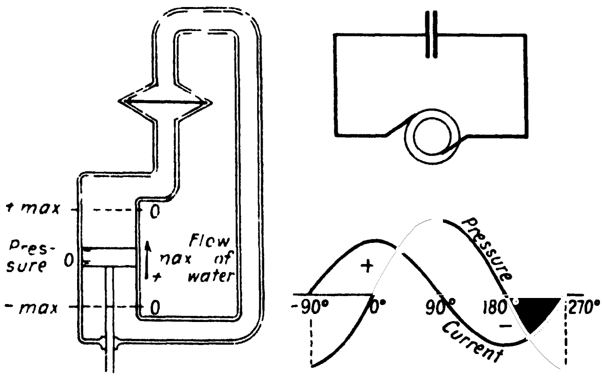


Fig. 410. — Hydraulic Analog of Condensive Circuit.

its middle position or the point of zero pressure; these facts are noted in the figure.

Returning to the electric circuit, if a sinusoidal E. M. F. is impressed upon a circuit containing a condenser, the current flow will be sinusoidal. This flow will be in the positive direction from the negative maximum to the positive maximum of pressure, and in a negative direction from the positive maximum to the negative maximum of pressure, as just described. This condition requires that the zero values of current occur at the maximum values of pressure, and since the curves are both sinusoids, their relation may be plotted as in the figure. It is seen that the *current leads the impressed E. M. F.* by 90°.

The condenser is completely charged at the instant of maximum positive pressure, discharged at the instant of zero pres-

sure, fully charged in the opposite direction at the instant of maximum negative pressure, and finally discharged at the instant of the next zero pressure. Thus the charge is zero at the maximum current flow, and a maximum at zero current or when the current reverses.

345. Impedance of a Condensive Circuit. — The alternating voltage impressed upon a circuit containing both resistance and capacitance may be considered as composed of two components: one, required to overcome the resistance, and the other, required to overcome the capacitive reactance. The first is in phase with the current and is equal to $E_r = RI$. The latter lags 90° behind the current (Fig. 410) and has a magnitude of $E_c = \frac{1}{2\pi fC} \times I$. These relations are indicated in the vector diagram of Fig. 411. The resultant of these components is the impressed electromotive force E; its value can be found by extracting the square root of the sum of the squares of the other two sides of the triangle, that is

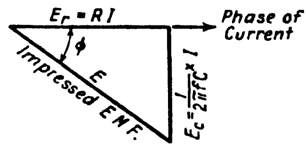


Fig. 411. — Components of E. M. F. Impressed on Condensive Circuit.

$$E = \sqrt{E_r^2 + E_c^2}, \qquad (130).$$

or

$$E = \sqrt{(I \times R)^2 + \left(I \times \frac{1}{2\pi fC}\right)^2} \qquad (131).$$

Factoring out the current, the impressed voltage becomes

$$E = I\sqrt{R^2 + \left(\frac{1}{2\pi fC}\right)^2} = I\sqrt{R^2 + X_c^2}.$$

The impedance of a condensive circuit may be expressed as

$$Z = \sqrt{R^2 + \left(\frac{1}{2\pi fC}\right)^2} = \sqrt{R^2 + X_c^2}, \qquad (132).$$

and the relation between capacitive reactance, resistance and impedance may be shown also by a triangle similar to that of Fig. 411. It will be observed in Fig. 412 (a) that the line representing capacitive reactance projects downward from the horizontal line, while the inductive reactance line in Fig. 412 (b)

projects upward as it does in Fig. 407; this indicates that the properties of inductance and capacitance are opposite in effect.

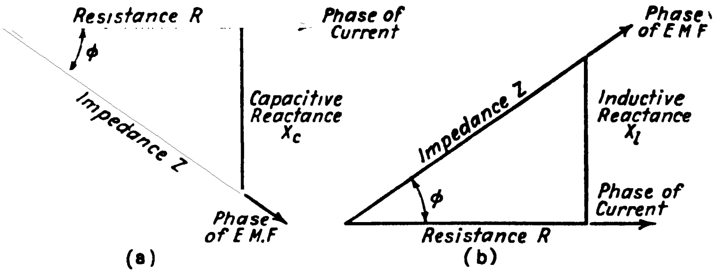


Fig. 412. — Relation between Resistance, Reactance and Impedance.
(a) Condensive circuit (b) Inductive circuit

Problem 139. – A resistance of 150 ohms is connected in series with a condenser of 25 microfarads capacitance to a 60-cycle supply of alternating current. What is the impedance of the circuit?

From Problem 138, the reactance of the condenser is 106.38 ohms.

By Formula (132), the impedance of the circuit is

$$Z = \sqrt{150^2 + 106.38^2} = \sqrt{33{,}821} = 183.9 \text{ ohms.}$$

346. Angle of Lag or Lead. In a circuit containing resistance and inductance the current lags behind the impressed E. M. F., the amount of lag depending upon the relative magnitude of the resistance and reactance. The lag is measured as an angle, called the *angle of lag*. It is customary to consider a cycle analogous to a circle, and to divide it into so-called *electrical degrees;* thus a quarter of a cycle is 90°, a half cycle 180°, and so on. This is convenient in that the phase of the current with respect to the E. M. F. may be expressed in degrees of a circle instead of parts of a cycle. In Fig. 412 (b) it appears that the current lags behind the impressed E. M. F. by the angle ϕ: this angle is termed the *angle of lag* of the current in the circuit, the angle here being 35°. The tangent of this angle is equal to the inductive reactance ÷ resistance; hence, *if the resistance and inductive reactance in a circuit are both known, the angle of lag may be calculated from*

$$\tan \phi = \frac{\text{reactance}}{\text{resistance}} = \frac{X_l}{R} = \frac{2\pi f L}{R} \quad . \quad . \quad . \quad . \quad . \quad \textbf{(133)}.$$

From the relation $\frac{2\pi fL}{R}$, it is seen that the larger the reactance, compared with the resistance, the larger will be the angle of lag, and if the reactance is small in comparison with the resistance the angle of lag will be small, the current then being nearly in phase with the impressed E. M. F.

Problem 140. By what angle would the current lag behind the 25-cycle impressed E. M. F. in a circuit in which the resistance is 4 ohms and the inductance is 0.048 henry?

Here $X_l = 2\pi fL = 7.53$ ohms and R = 4 ohms, therefore, by Formula (133)

$$\tan\phi = \frac{2\pi fL}{R} = \frac{7.53}{4} = 1.88.$$

From Table XI, page 236 the angle having a tangent of 1.88 is 62°; therefore the current lags 62° behind the impressed E. M. F.

The effect of capacitance in a circuit is exactly the opposite to that of inductance, for capacitance makes the current lead the impressed E. M. F. while inductance makes the current lag behind that E. M. F. The tangent of the angle of lead is seen in Fig. 412 (a) to be the capacitive reactance ÷ resistance, hence, *if the resistance and capacitive reactance in a circuit are both known, the angle of lead may be calculated from*

$$\tan\phi = \frac{\text{reactance}}{\text{resistance}} = \frac{X_c}{R} = \frac{\frac{1}{2\pi fC}}{R} = \frac{1}{2\pi fCR} \qquad \textbf{(134).}$$

Problem 141. — What is the angle of current lead in the circuit of Problem 139?

By Formula (134) $\tan\phi = \frac{X_c}{R} = \frac{106.38}{150} = 0.709$. Whence $\phi = 35°$.

The cosine of the angle of lag or lead is the power factor of the circuit. This quantity may be defined as the ratio of the actual power expended in an alternating-current circuit as measured by a wattmeter to the product of the voltage and current as measured respectively by a voltmeter and an ammeter. Since the cosine of the angle in Fig. 412 is the resistance R divided by the impedance Z, it follows that the power factor in an inductive or in a condensive circuit is

$$\text{Power factor} = \cos\phi = \frac{R}{Z} \quad \textbf{(135).}$$

347. Condensers Connected in Parallel and in Series. — Connecting condensers in parallel is equivalent to increasing the number of plates in one of them. An increase in the number of plates results in increasing the quantity of electricity necessary to raise the potential difference between the terminals of a condenser one volt, that is an increase of capacitance results. If two 1-microfarad condensers are connected in parallel, the total capacitance will be 2 microfarads. In general, if C_1, C_2, C_3, etc. are the individual capacitances of condensers that are connected in parallel, the total or joint capacitance will be

$$C = C_1 + C_2 + C_3 + \ldots \ldots \ldots \quad \textbf{(136)}.$$

Consider three condensers to be connected in series as shown in Fig. 413, with E volts impressed across the outside terminals.

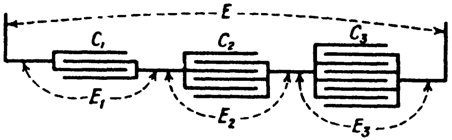


Fig. 413. — Condensers Connected in Series.

If a quantity of positive electricity, Q, flows into the left side of C_1, it will induce and keep bound an equal negative quantity on the right side of C_1, and will repel an equal positive quantity of electricity. This last quantity will constitute the charge for the left side of C_2. This procedure is repeated in the case of each of the condensers. It is thus clear that the quantity of charge in each condenser is Q. The impressed electromotive force E must necessarily be the sum of the potential differences on the separate condensers, that is, the sum of E_1, E_2, and E_3. Then

$$E = E_1 + E_2 + E_3.$$

But by Formula (128)

$$E = \frac{Q}{C}, \quad E_1 = \frac{Q}{C_1}, \quad E_2 = \frac{Q}{C_2}, \text{ etc.,}$$

therefore

$$\frac{Q}{C} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}.$$

Dividing through by Q,

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3},$$

or
$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}} \quad \ldots \ldots \ldots \quad (137).$$

It is interesting to note that the formulæ for *capacitances* in parallel and in series are just the reverse of those for *resistances* in parallel and in series respectively.

Problem 142. — What capacitances can be formed from two condensers, one being of 0.4 and the other of 0.6 microfarad?

When connected in parallel the joint capacitance is 0.4 + 0.6 = 1.0 mf.

When connected in series the total capacitance is less than either, in this case

$$C = \frac{1}{\frac{1}{0.4} + \frac{1}{0.6}} = \frac{1}{2.50 + 1.67} = \frac{1}{4.17} = 0.24 \text{ mf.}$$

The four capacitances available are 0.24, 0.4, 0.6 and 1.0 microfarads.

348. Condensers — Condensers are used in a variety of electrical circuits, especially in those relating to electrical communication. In telephony some standard sizes are 0.05, 0.5, 1, and 2 microfarads, the condensers being mounted in thin rectangular iron cases. These condensers have two tin-foil strips many feet long and about 3 inches wide and four paper strips slightly exceeding these dimensions. The strips are placed together, alternately, two of paper and one of tin foil, and are wound on a collapsible mandrel, thus forming a compact condenser of cylindrical form about 3.5 inches long. It is then immersed in a closed tank of molten paraffin and the air is exhausted from the tank; upon the subsequent admission of the air the paraffin is forced into the innermost recesses of the condenser.

In duplex and quadruplex telegraph circuits condensers are used with resistances to form *artificial lines* which resemble electrically the actual line conductors, ¶ 390. Use is made in radio receiving circuits of fixed condensers with their plates separated by mica or paper, and of variable condensers with semicircular plates separated by air. The capacitances of the latter range up to 0.005 microfarad according to the amount of separation and the number of plates.

Condensers are used in improving the power factor on the lines of electric service companies, and when so used are termed

static condensers to distinguish this method of power-factor correction from the one utilizing synchronous motors or *synchronous condensers*, ¶ 373. Static condensers are found to be more economical than synchronous condensers in sizes below about 500 kilovolt-amperes, and at frequencies from 40 to 125 cycles. A 2.5-microfarad condenser unit for use on a 60-cycle, 2300-volt static condenser takes a current according to ¶ 343 of $I = 2\pi CEf = 6.28 \times 0.0000025 \times 2300 \times 60 = 2.17$ amperes; its rating is therefore $2.17 \times 2300 = 5000$ volt-amperes or 5 kv-a. The number of such units is determined by the improvement in power factor desired as expressed in kv-a.

349. Circuits having Inductance, Capacitance and Resistance. — When a circuit contains both inductance and capacitance, the net reactance, X, is equal to the arithmetical difference between the inductive reactance, X_l, and the capacitive reactance, X_c, or $X = X_l - X_c$.

Therefore the impedance of a circuit containing inductance, capacitance and resistance is equal to

$$\sqrt{\text{resistance}^2 + (\text{inductive reactance} - \text{capacitive reactance})^2}$$

$$\text{or} \qquad Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (X_l - X_c)^2} \quad . \quad . \quad . \quad \textbf{(138)}.$$

Problem 143. What would be the combined impedance of a circuit, having a coil of 4 ohms resistance and of 0.01 henry inductance in series with a condenser of 25 microfarads capacitance, to an alternating current of 120 cycles?

By Formula (120) $X_l = 2\pi fL = 6.28 \times 120 \times 0.01 = 7.53$ ohms.

By Formula (129)

$$X_c = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 120 \times 0.000025} = 53.07 \text{ ohms.}$$

By Formula (138) $Z = \sqrt{R^2 + (X_l - X_c)^2} = \sqrt{4^2 + (7.53 - 53.07)^2}$

$$= \sqrt{16 + 2073} = 45.71 \text{ ohms}$$

The foregoing may be made clearer by the use of the triangular diagram shown in Fig. 414, which shows the relation between reactance, resistance and impedance. The net reactance X of the circuit is indicated as the *difference* between the lengths of the lines representing inductive and capacitive reactances. In the figure the capacitive reactance, X_c, is one-third as great as the inductive reactance, X_l; the resultant or net reactance, X, therefore, is two-thirds as great as the in-

ductive reactance, and the impedance line is drawn from the left-hand end of the base line to a point two-thirds up along the line representing inductive reactance. The dotted line, a, shows what the impedance would be if there were no capacitance in the circuit, and the dotted line, b, shows what the impedance would be if the inductance were not present.

It is obvious that when X_l and X_c are equal, the difference between them is zero, making the impedance, Z, equal to $\sqrt{R^2}$, which of course is R. When this is the case the circuit operates as though there were neither inductance nor capacitance present, the current rising and falling in unison with the E. M. F. Referring to Fig. 114, if the lines X_l and X_c were of equal length their difference would be zero, and the impedance line would be identical with the resistance line. Such a circuit is said to be in *resonance* with the impressed alternating E. M. F., ¶ 355.

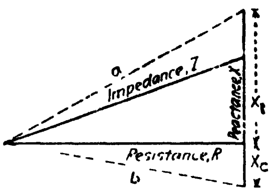


Fig. 114 Resultant Reactance and Impedance of a Circuit Containing Inductance and Capacitance.

350. Ohm's Law for Alternating-Current Circuits. In dealing with direct-current systems the relation existing between the pressure, current strength and resistance is fully expressed by Ohm's Law, *i.e.*, $I = E \div R$. This law, however, cannot be applied in the same form to alternating-current circuits, since the current no longer depends simply upon the resistance and E. M. F., but also depends on the frequency, f, the inductance, L, and the capacitance, C, that may be contained in the circuit. It follows from the derivations of Formulæ (126) and (129) that Ohm's Law for alternating-current circuits may be summarized as below:

I — *The current in any circuit is equal to the electromotive force applied to the circuit divided by the impedance of the circuit.*

Let E = E. M. F. or the pressure applied to any circuit,
Z = impedance of the circuit expressed in ohms,
I = current strength in that circuit; then,

$$I = \frac{E}{Z} \quad \ldots\ldots\ldots\ldots \quad (139).$$

This modification of Ohm's Law, Formula (139), applies to alternating currents flowing in any circuit and bears the same relation and importance to alternating-current problems that Ohm's Law does to direct-current problems.

Problem 144. — (*a*) What current will flow through a coil of 7 ohms resistance and 24 ohms reactance when connected across a 60-cycle E. M. F. of 110 volts? (*b*) What current would flow if the coil were connected across a 110-volt direct-current supply circuit?

By Formula (127) $Z = \sqrt{R^2 + X_L^2} = \sqrt{7^2 + 24^2} = \sqrt{49 + 576} = 25$ ohms.

By Formula (139) $I = \frac{E}{Z} = \frac{110}{25} = 4.4$ amperes (*a*).

By Formula (27) $I = \frac{E}{R} = \frac{110}{7} = 15.7$ amperes (*b*).

II — *The electromotive force of known frequency required to maintain a certain current in a circuit of known impedance, is numerically equal to the product of the current and the impedance.*

Problem 145. — What E. M. F. would be required from an alternator of 60 cycles to send a current of 5 amperes through a coil of 4 ohms resistance and 0.02 henry inductance?

By Formula (126) $Z = \sqrt{R^2 + (2\pi fL)^2} = \sqrt{4^2 + (6.28 \times 60 \times 0.02)^2}$

$= \sqrt{4^2 + 7.53^2} = \sqrt{16 + 56.7} = 8.52$ ohms.

Consequently $E = I \times Z = 5 \times 8.52 = 42.6$ volts.

III — *The impedance, to be inserted in any circuit so that a given current will flow by reason of a known pressure, is equal to the pressure to be applied divided by the current that is to be maintained.*

Problem 146. — What would be the impedance of a circuit having a pressure of 500 volts across it and having a current of 6.5 amperes flowing through it?

The impedance is $Z = \frac{E}{I} = \frac{500}{6.5} = 76.9$ ohms.

The similarity between the foregoing equation and Ohm's Law is apparent. The value of the *resistance* of a circuit may be calculated merely from the physical dimensions of the wire, but not so with *impedance* (the total opposition offered to the flow of an alternating current). Beside the frequency of the impressed voltage, the two factors which determine the impedance,

namely inductance and capacitance, both depend upon the *form* of the circuit as well as upon the dimensions of the conductor.

Impedance may be measured by the volt-ammeter method in the same way as resistance is measured in a direct-current circuit (¶ 228), using, of course, an alternating-current voltmeter and ammeter, the impedance being calculated from $Z = E \div I$. Knowing the ohmic resistance of the circuit or device, the *reactance* can be calculated from Formula (127), and thereafter the *inductance* can be found from Formula (121), provided the frequency of the current is known.

351. Impedances in Series. — When several reactive devices are connected in series to an alternating-current circuit, the total impedance of the group cannot be determined by adding the individual impedances arithmetically, as is done with resistances in direct-current work, because the voltages causing current

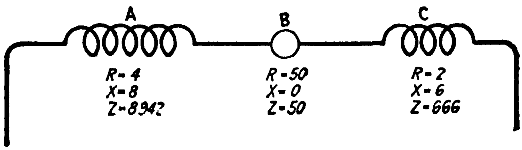


Fig. 415. — Impedances in Series.

flow through these devices are not in phase with each other. Instead, the impedance of each device must be resolved into its component resistance and reactance, these components are then added separately, and thereafter the total impedance is determined from these sums.

TO FIND THE TOTAL IMPEDANCE OF A NUMBER OF IMPEDANCES CONNECTED IN SERIES:

Find the sum of the resistances in the circuit, and the sum of the reactances; then find the sum of the squares of the total resistance and the total reactance, and extract the square root of this value.

$$Z = \sqrt{(R_1 + R_2 + \text{etc.})^2 + (X_1 + X_2 + \text{etc.})^2} \quad . \quad . \quad (140).$$

Problem 147. — One non-inductive and two inductive devices are connected in series Fig 415, the coils A and C being the inductive parts of the circuit. The values of the resistance, reactance and impedance of each part of the circuit are inscribed in the figure. What is the total impedance of the devices so connected?

The non-inductive device B has, of course, no reactance, so that its impedance is equal to its resistance. If the three impedances noted in the figure had been added the result would have been 65.6 ohms; this is incorrect because the vectors which represent these impedances do not lie in one direction. The correct answer for the total impedance is found by Formula (140) to be

$$Z = \sqrt{(R_1 + R_2 + R_3)^2 + (X_1 + X_2 + X_3)^2}$$
$$= \sqrt{(4 + 50 + 2)^2 + (8 + 0 + 6)^2} = \sqrt{56^2 + 14^2} = 57.7 \text{ ohms.}$$

352. Impedances in Parallel. — When inductive devices are connected in parallel, the joint impedance of any given group of devices is determined by a method similar to that described in ¶ 351; but instead of considering the separate resistances and reactances, the opposite properties, *conductance* and *susceptance*, are considered. In direct-current work, conductance, ¶ 107, is the reciprocal of resistance; in alternating-current work, the conductance is taken as the resistance divided by the square of the impedance. Similarly, the susceptance is the reactance divided by the square of the impedance.

To find the conductance (G): *Divide the resistance by the sum of the squares of the resistance and reactance.*

$$G = \frac{R}{R^2 + X^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(141)}.$$

To find the susceptance (S): *Divide the reactance by the sum of the squares of the resistance and reactance.*

$$S = \frac{X}{R^2 + X^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(142)}.$$

The reciprocal of impedance is called *admittance*, represented by Y, and is equal to the current divided by the E. M. F., or

$$Y = \frac{1}{Z} = \frac{I}{E} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(143)}.$$

The relation between *admittance*, *conductance* and *susceptance* is precisely the same as that between impedance, resistance and reactance shown in Fig. 416. The formula for admittance is therefore analogous to that for impedance, wherein conductance is substituted for resistance and susceptance for reactance; thus,

$$Y = \sqrt{G^2 + S^2} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(144)}.$$

In order to verify the correctness of the preceding equations, substitute the values of G, S and Y in Formula (144). Thus

$$\frac{1}{Z} = \sqrt{\frac{R^2}{(R^2 + X^2)^2} + \frac{X^2}{(R^2 + X^2)^2}} = \frac{\sqrt{R^2 + X^2}}{R^2 + X^2} = \frac{1}{\sqrt{R^2 + X^2}},$$

which shows that $Z = \sqrt{R^2 + X^2}$ as before.

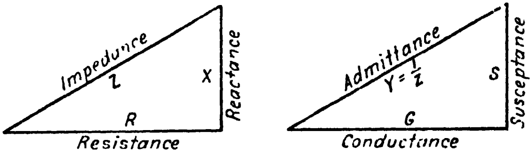


Fig. 416. — Similarity between Impedance and Admittance Triangles

To FIND THE JOINT IMPEDANCE OF A NUMBER OF DEVICES CONNECTED IN PARALLEL:

(1) *Find the conductances and susceptances of the individual devices,* (2) *find the sum of the conductances and the sum of the susceptances,* (3) *extract the square root of the sum of the squares of the total conductance and total susceptance, which gives the admittance,* (4) *find the reciprocal of the admittance to obtain the joint impedance of the circuit.* Again,

$$\text{Joint impedance} = \frac{1}{\sqrt{(G_1 + G_2 + \text{etc.})^2 + (S_1 + S_2 + \text{etc.})^2}}$$

Problem 148. — What would be the joint impedance of the three devices in Fig. 415 if they were connected in parallel?

The conductance of coil A is, by Formula (141),

$$G = \frac{R}{R^2 + X^2} = \frac{4}{16 + 64} = 0.05,$$

and its susceptance, by Formula (142), is

$$S = \frac{X}{R^2 + X^2} = \frac{8}{16 + 64} = 0.10$$

Similarly, the conductance of coil C is

$$G = \frac{2}{4 + 36} = 0.05,$$

and its susceptance is

$$S = \frac{6}{4 + 36} = 0.15.$$

Since the lamp B is non-inductive, its conductance is equal to the reciprocal of its resistance, $\frac{1}{50} = 0.02$. Its susceptance is zero.

Sum of all the conductances = 0.05 + 0.02 + 0.05 = 0.12.

Sum of all the susceptances = 0.10 + 0.15 = 0.25.

Admittance (Y), by Formula (144), is $Y = \sqrt{G^2 + S^2} = \sqrt{0.12^2 + 0.25^2}$ = 0.277; and the impedance is

$$\frac{1}{Y} = \frac{1}{0.277} = 3.6 \text{ ohms.}$$

353. Polyphase Circuits. — It has been stated in ¶ 332 that a two-phase alternator develops two alternating E. M. F.'s of the same value but 90° (or a quarter of a cycle) apart. Such a generator may be looked upon as composed of two separate single-phase alternators of the same size, the E. M. F.'s of which are maintained mechanically at a phase difference of 90°. Let these alternators be denoted by 1 and 2, Fig. 417, and assume that the E. M. F. of alternator 2 lags 90° behind that generated

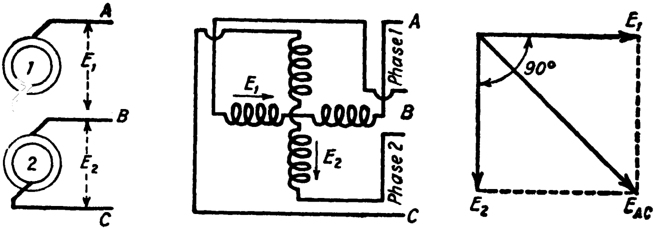


Fig. 417. — Voltage Relations in a Two-phase System.

in alternator 1. The E. M. F. relations may be represented graphically by the arrows E_1 and E_2 on the diagrammatic representation of the two-phase alternator at the center of the figure, lag being clockwise.

Now consider the lower terminal of alternator 1 and the upper terminal of alternator 2 to be connected at B, thus forming a two-phase, three-wire system. The voltage across AC is due to the E. M. F.'s produced in both alternators, and its value is determined by the vector diagram at the right in which E_1 and E_2 represent the effective values of the voltages produced in armature windings 1 and 2 respectively. Adding these equal voltages at 90° difference in phase yields the diagonal E_{AC} which has a value of $\sqrt{2}\, E_1$ volts. Thus the voltage across

line wires AC is $\sqrt{2}$ or 1.41 times the voltage across lines AB or BC.

Similarly, consider a three-phase alternator to consist of three single-phase generators having equal E. M. F.'s maintained at successive phase displacements of 120°. In the upper half of

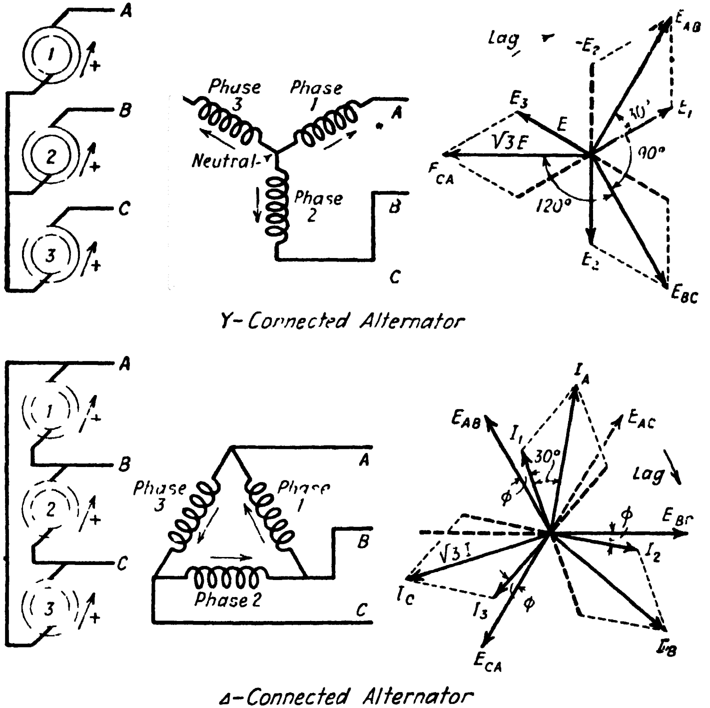


Fig. 418. — Voltage Relations in a Three-phase System.

In the Y-connection (top) the voltage across any two wires is 1.73 times the voltage of the phase winding. In the Δ-connection (bottom) the current in each line is 1.73 times the current in the phase winding.

Fig. 418 these three alternators are shown connected one to each line wire, and their other terminals are joined to form the *neutral point* of the system. This so-called Y-connection is visualized at the center; such a diagram is used to represent a Y-connected three-phase alternator. Let the directions of the E. M. F.'s in

the three armature coils, as their axes successively pass a given fixed point, be positive, as shown by the arrows. Then, the phase relations of the armature electromotive forces will be represented as in the vector diagram at the right, in which E_2 lags behind E_1 by 120°, and E_3 lags behind E_2 by 120°. The potential differences between the three line wires may then be determined by graphical construction.

The voltage between lines A and B is equal to vector E_1 *minus* vector E_2, minus because these voltages are directed away from the neutral point and therefore oppose each other While E_1 and E_2 are equal voltages, their difference is not zero, because they are directed at an angle to each other. To subtract vector E_2 from E_1, change the sign of E_2 (that is, reverse it or turn it through 180°) and then add it to E_1. This process is shown in the diagram and the result is E_{AB} leading E_1 by 30°. Similarly, E_{BC} equals E_2 minus E_3 and lags 90° behind E_1; E_{CA} equals E_3 minus E_1 and lags 210° behind E_1. Calling the E. M. F. generated in each armature coil E volts, the magnitudes of E_{AB}, E_{BC} and E_{CA} will each be $\sqrt{3}$ E or 1.73 E; this fact may be verified by scaling the diagram or by geometrical proof.

In the lower part of the same figure (Fig. 418) are indicated the corresponding conditions for a different connection of the three single-phase alternators. Here the alternators are connected in delta (Δ), thus forming a three-phase mesh- or Δ-connected system. The E. M. F. across two line wires is that produced by one alternator only and is E volts, and if all the other conditions remain unchanged, E_{BC} will lag 120° behind E_{AB}, and E_{CA} will lag 120° behind E_{BC}. Assume the three phases to be equally loaded, that is, the three loads (one across each pair of line wires) have the same resistance and the same reactance. The arrows represent positive current flow in the coils, as their axes successively pass a fixed point, and the values of the currents in the lines may be determined as shown in the vector diagram, where ϕ is the angle of lag. It is seen that I_A equals I_1 minus I_3 and lags 30° + ϕ behind E_1 or E_{AB}. Similarly I_B equals I_2 minus I_1 and lags 150° + ϕ behind E_1; and I_C equals I_3 minus I_2 and leads E_1 by 90° − ϕ. The magnitude of each line current is $\sqrt{3}$ I or 1.73 I, where I is the current in each alternator or phase winding.

354. Power in Polyphase Systems. — The power expended in a single-phase circuit on which the E. M. F. is E volts and in which the current is I amperes, is given by Formula (118) as

$$P = EI \cos \phi,$$

where the factor $\cos \phi$ is the power factor of the circuit, and where ϕ is the angle of phase difference between the current and the impressed E. M. F. Both E and I are effective values and P is the power in watts. The measurement of power in a single phase circuit is described in ¶ 333.

Problem 149. — An alternator generating an E. M. F. of 1100 volts at a frequency of 60 cycles supplies energy to a system that has a resistance of 125 ohms and an inductance of 0.5 henry (*a*) Find the value of the current. (*b*) Find the angle of lag. (*c*) Determine the power factor. (*d*) Calculate the apparent power and the true watts.

By Formula (126) the impedance is

$$Z = \sqrt{R^2 + (2\pi fL)^2} = \sqrt{125^2 , (6.28 \times 60 \times 0.5)^2} = 226.1 \text{ ohms.}$$

By Formula (139) the current is

$$I = \frac{E}{Z} = \frac{1100}{226.1} = 4.86 \text{ amperes. (a)}$$

By Formula (133) the tangent of the angle of lag is

$$\tan \phi = \frac{2\pi fL}{R} = \frac{6.28 \times 60 \times 0.5}{125} = \frac{188.4}{125} = 1.51.$$

From Table XI, the angle whose tangent is 1.51 is = 56.5°. (b)

By Formula (135) the power factor is

$$\cos \phi = \frac{R}{Z} = \frac{125}{226.1} = 0.55 \text{ or } 55 \text{ per cent. (c)}$$

Apparent power is

$$P = E \times I = 1100 \times 4.86 = 5346 \text{ volt-amperes. (d)}$$

Actual power, by Formula (118), is

$$P = E \times I \times \cos \phi = 1100 \times 4.86 \times 0.55 = 2940 \text{ watts. (d)}$$

The power delivered to the receiving circuits of a two-phase, four-wire system can be measured by two wattmeters, one connected in each phase. The sum of their readings is the total power supplied. If the load is balanced, one of the wattmeters may be dispensed with, and the total power is then double the reading of the other. This wattmeter may also be used to measure the power factor of the balanced load. When connected in one circuit, the wattmeter reading is

$$P_1 = EI \cos \phi;$$

when the pressure coil is transferred to the other phase, leaving the connection of the current coil unchanged, the reading is

$$P_2 = EI \cos (90° - \phi) = EI \sin \phi,$$

because of the 90° phase difference between the two E. M. F.'s. Since the sine of the angle divided by the cosine of the same angle gives its tangent, it follows from these equations that

$$\tan \phi = \frac{\sin \phi}{\cos \phi} = \frac{P_2}{P_1} \quad \ldots \ldots \ldots \ldots \quad \textbf{(145).}$$

From tables the angle ϕ and thereafter $\cos \phi$ (power factor) may be determined.

Measurement of power in a two-phase three-wire system can be measured by two wattmeters connected as in Fig. 419 (a) whether the load is balanced on the two phases or not. The total power expended is the sum of the instrument readings.

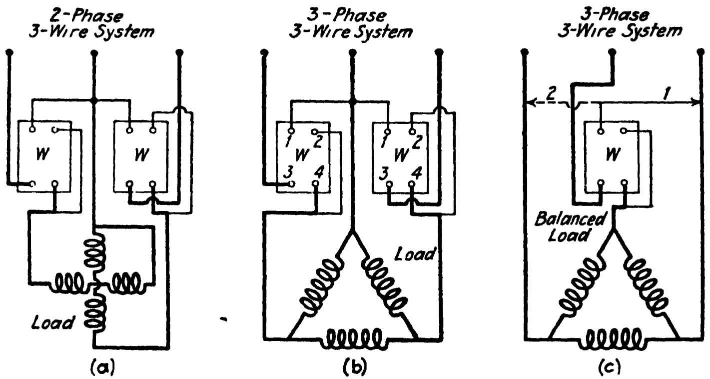


Fig. 419. — Measurement of Power in Two- and Three-phase Circuits.

An accurate method for the determination of the power in unbalanced three-phase systems, avoiding the necessity of a neutral point, involves the use of two wattmeters connected as in Fig. 419 (b). The load circuits may be connected either in Δ or Y. The algebraic sum of the instrument indications is, as before, the total power supplied. In some cases the lesser reading will be negative. To determine the correct sign of the readings, the wattmeters may be interchanged so that the wires shown in the

figure will connect with like-numbered wattmeter terminals. Should the reading of either wattmeter be reversed by this change, then the original reading of that meter is negative.

Another method of measuring power in a *balanced* three-phase system, either Δ- or Y-connected, is based upon the assumption that both pressures and currents vary sinusoidally. No neutral point is required, and the connections are shown in Fig. 419 (c). The pressure coil is connected from the wire which includes the current coil to first one of the other wires, and then to the remaining wire. The angular displacements between the current in any line wire and the E. M. F.'s between it and the other line wires are $30° + \phi$ and $30° - \phi$, as will become evident from an inspection of Fig. 418. The readings of the wattmeters are then

$$P_1 = \sqrt{3}\ EI \cos (30° + \phi),$$

and

$$P_2 = \sqrt{3}\ EI \cos (30° - \phi),$$

where E is the E. M. F. generated and I is the current flowing in each armature coil of the alternator supplying the load circuit. The algebraic sum of the readings is

$$P_1 + P_2 = \sqrt{3}\ EI \left[\cos (30° + \phi) + \cos (30° - \phi)\right] = 3\ EI \cos \phi,$$

which is the total power delivered. When ϕ is greater than 60°, P_1 becomes negative, hence care is required to avoid confusion of signs at power factors less than 50 per cent.

Representing the E. M. F. between any two line wires by E_l, and the current in each line by I_l then, since either $E_l = \sqrt{3}\ E$ (Y-connection) or $I_l = \sqrt{3}\ I$ (Δ-connection), by dividing the previous results by $\sqrt{3}$ there is obtained as the total power delivered

$$P = P_1 + P_2 = \sqrt{3}\ E_l\ I_l \cos \phi \quad . \quad . \quad . \quad . \quad \textbf{(146)}.$$

Problem 150. — A three-phase alternator is connected to a balanced receiving circuit of 80 per cent power factor. Determine the magnitude of the power supplied by the alternator when the voltage across the line wires is 150 volts and the current in each line is 20 amperes.

The line voltage $E_l = 150$ volts, the line current $I_l = 20$ amperes, and the power factor $\cos \phi = 0.80$; therefore by Formula (146) the power supplied is

$$P = \sqrt{3} \times 150 \times 20 \times 0.80 = 4160 \text{ watts.}$$

355. Resonance. — If an alternating voltage is impressed upon a circuit comprising a coil and a condenser connected in series, the current that will flow will depend upon the resistance and inductance of the coil, upon the capacitance of the condenser, and upon the frequency of the impressed E. M. F. This current value is expressed by Formula (139), which becomes

$$I = \frac{E}{\sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}},$$

where R is the resistance in ohms, L is the inductance in henrys, and C is the capacitance in farads. Varying either circuit constant L or C, or changing the frequency f of the alternating voltage, will alter the impedance of the circuit and affect the current strength. The maximum current would be obtained when the factors L, C and f are so related that the inductive reactance $2\pi fL$ is equal to the capacitive reactance $\frac{1}{2\pi fC}$, for then the total reactance is zero and the impedance of the circuit is merely R. This condition for maximum current in a *series circuit*, requiring

$$2\pi fL = \frac{1}{2\pi fC},$$

is called *resonance*. The natural frequency of the circuit is obtained from the foregoing equation by solving for f, yielding

$$f = \frac{1}{2\pi\sqrt{LC}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(147)}.$$

Thus the condition of resonance is attained when the frequency of the impressed E. M. F. coincides with the natural frequency of the circuit.

Consider a circuit having a resistance of 40 ohms, an inductance of 1.274 millihenry and a capacitance of 0.002 microfarad. Its natural frequency is given by Formula (147) as

$$f = \frac{1}{2\pi\sqrt{0.001274 \times 0.000000002}} = \frac{1}{2\pi \times 0.00000159} = 100{,}000 \text{ cycles}.$$

The following table gives the inductive, capacitive and total reactances of this circuit for several frequencies over the range from $\frac{1}{3}$ to 3 times the natural frequency:

Table XXI. Variation of Reactance with Frequency

Frequency f cycles	Inductive Reactance $X_L = 2\pi fL$ ohms	Capacitive Reactance $X_C = \frac{1}{2\pi fC}$ ohms	Total Reactance $X = X_L - X_C$ ohms
30,000	240	2660	− 2420
40 000	320	2000	− 1680
60 000	480	1330	− 850
100 000	800	800	0
150 000	1200	530	670
200 000	1600	400	1200
300 000	2400	266	2134

It is seen that at relatively low frequencies the capacitive reactance predominates over inductive reactance, while at relatively high frequencies the inductive reactance is the more important.

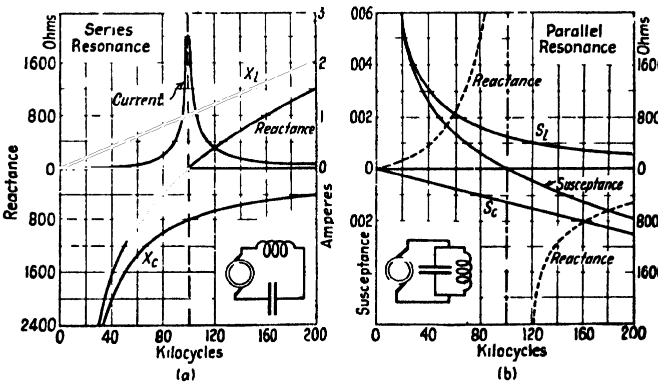


Fig 320 — Series and Parallel Resonance
(a) Reactance curves of a series circuit together with the resonance curve of current
(b) Susceptance and reactance curves of a parallel circuit

portant. Further, the resistance of the circuit (40 ohms in this illustration) is of negligible effect except at resonance. These values of reactance are plotted in Fig. 420 (*a*) against frequency in kilocycles (1 kilocycle = 1000 cycles). The straight line

marked X_l represents the inductive reactance and the curve marked X_c represents the capacitive reactance; the sum of the two is shown by the curve marked "Reactance," and this curve crosses the axis at the natural frequency of 100 kilocycles.

A curve showing the variation of current with frequency is called a *resonance curve,* and such a curve is plotted on the same diagram for the assumption that the impressed E. M. F. is 100 volts. This curve would rise to infinity at the resonant frequency were it not for the resistance of the circuit. At resonance the potential difference across the condenser may greatly exceed the impressed voltage; its value in the numerical illustration is $E_c = \frac{1}{2\pi fC} \times I = 800 \times 2.5 = 2000$ volts. This pressure is balanced by the potential difference across the coil, namely $E_l = 2\pi fL \times I = 800 \times 2.5 = 2000$ volts. Hence, when a series circuit becomes resonant with the applied voltage, potential differences may be set up which are sufficient to puncture the insulation of the circuit. In radio circuits carrying minute currents, resonance is sought for in order to develop sufficient voltages; this process, involving adjustment of the inductance or capacitance of the circuit, is called *tuning.*

When a coil and a condenser are placed in parallel connection with an alternator, the behavior is quite different from that of the series arrangement just considered. Ignoring the resistance of the circuit, its total admittance will be the same as the total susceptance, which then becomes

$$S = S_l - S_c = \frac{1}{X_l} - \frac{1}{X_c},$$

by making R = 0 in Formula (142). The inductive susceptance $S_l = \frac{1}{2\pi fL}$, and the capacitive susceptance $S_c = 2\pi fC$, for the same values of L and C as used in the preceding illustration are plotted separately in Fig. 420 (*b*), and their total is shown by the curve marked Susceptance. By taking reciprocals of points on this curve there results the two-branch curve marked Reactance. The susceptance curve crosses the zero axis at the frequency of parallel resonance, and there both branches of the reactance curve rise to infinity. Consequently the current in

the main circuit at that frequency is zero, still assuming negligible resistance; the current curve would be similar to the curve of total susceptance except that the part below the axis would lie an equal distance above it. In this parallel arrangement at resonance, relatively large currents may flow in the inductive and capacitive branches and sometimes damage may result by the overloading and burning-out of the conductors in or between these branches. Parallel resonance is made use of in some communication circuits when current of definite frequency is to be suppressed.

Problem 151. — A solenoid has an inductance of 0.2 henry and a resistance of 10 ohms; it is connected in series with a 25-microfarad condenser. (*a*) Determine the natural frequency of the circuit. (*b*) What will be the impedance of the circuit at 60 cycles?

By Formula (147)

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{6.28\sqrt{0.2 \times 0.000025}} = \frac{1}{0.01405} = 71.1 \text{ cycles. } (a)$$

From ¶ 349, the impedance at 60 cycles is

$$Z = \sqrt{(10)^2 + \left(6.28 \times 0.2 \times 60 - \frac{1}{6.28 \times 0.000025 \times 60}\right)^2}$$

$$= \sqrt{100 + 961} = 32.6 \text{ ohms. } (b)$$

356. Electric Filters. — Circuits for augmenting and suppressing currents of a definite frequency were considered in the last section. Such series and parallel circuits containing inductance and capacitance may be considered the simplest types of more complicated networks that are used for controlling the strength of currents having a definite *range* of frequencies; such networks are called *electric filters.*

A filter which transmits currents of the lower frequencies and eliminates those of the higher frequencies is termed a *low-pass filter;* it consists of several meshes having series-connected inductances and shunt-connected capacitances as shown in Fig. 421 (*a*). A periodic network in which condensers are the series-connected elements and inductance coils are the shunt elements is called a *high-pass filter* (Fig. 421 *b*). A combination of these two types (shown at *c*) transmits currents above some predetermined frequency and below some higher selected frequency; they are called *band filters.*

Filters are used to smooth out the varying currents produced by rectifiers, to select currents of definite frequencies in carrier-current and radio transmission, and for the elimination of harmonics generated by vacuum-tube oscillators.

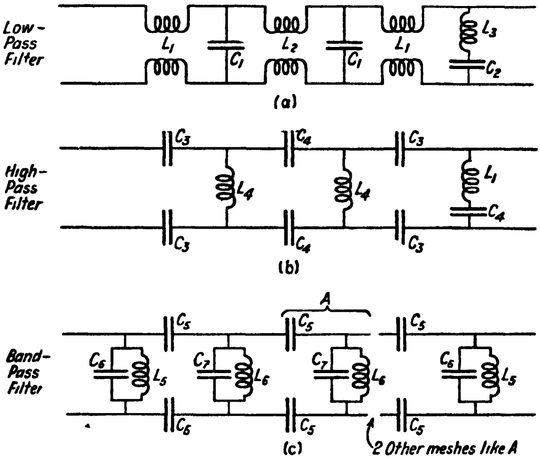


Fig. 421. — Types of Electric Filters.

The constants of a low-pass and a high-pass filter which, in combination, are used with a carrier-current composite set (as illustrated in Fig. 497), are given below for the symbols used in Fig. 421 (*a*) and (*b*):

L_1 =	0.0532 henry	$C_1 = 2C_4$ =	0 1711 microfarad
L_2 =	0 0658 "	C_2 =	0.0529 "
$L_3 = 2L_4$ =	0 0329 "	C_3 =	0 106 "

The left-hand terminals of these filters connect with the line of 600-ohm resistance and the right-hand terminals join with the terminal apparatus also of 600 ohms resistance. The cut-off frequency is 3000 cycles.

The constants of the band-pass filter shown in Fig. 421 (*c*) when designed to transmit only frequencies from 10,000 to 12,000 cycles between 600-ohm resistance lines are as follows

L_5 =	0.00186 henry	C_5 =	0.048 microfarad
L_6 =	0.00093 "	$2C_6 = C_7$ =	0.185 "

QUESTIONS

1. Why does inductance have such an important effect upon the strength of an alternating current?
2. Define the henry.
3. How would you represent graphically the relation existing between impedance, reactance and resistance?
4. If the frequency of an alternating E. M. F. that is impressed upon an inductive circuit is doubled how will the current be affected, the voltage remaining the same?
5. What are some uses for reactors?
6. What is meant by the capacitance of a line or circuit?
7. What effect has capacitance upon the flow of an alternating current?
8. Define the farad.
9. What is the essential difference between capacitive and inductive reactance upon the flow of an alternating current?
10. What factors beside resistance must be taken into consideration in determining the flow of alternating current and what do those factors depend upon?
11. What is the form of Ohm's Law for alternating-current circuits?
12. What determines the angle of current lag or lead?
13. What is the effect on capacitance of connecting two condensers in parallel? in series?
14. How can the impedance of a circuit be measured?
15. What is admittance? and what are its components?
16. State the method for obtaining the joint impedance of two devices connected in parallel.
17. Give a graphical illustration of the relations existing between the impressed E. M. F. and its components.
18. Define resistance, reactance and impedance.
19. Under what conditions can a current in a circuit lead the E. M. F. impressed upon it?
20. Knowing the values of the resistance and the inductance of a circuit, how would you determine the angle of lag for a current of given frequency?
21. What are the voltage relations in two- and in three-phase circuits?
22. Explain the Y and Δ methods of connecting alternator windings.
23. Show that the voltage between terminals of a three-phase Y-connected alternator is $\sqrt{3}$ times the voltage generated in the phase winding.
24. A three-phase alternator is connected to a balanced inductive load and the power is measured according to the method of Fig. 419 (*c*). What is the total power delivered to the receiving circuits if the observed indications of the wattmeter are 2200 and 2900 watts?
25. Give a diagram showing how the power supplied to a three-phase load may be measured.
26. What is meant by the natural frequency of a circuit and how is it expressed?

27. Distinguish between series and parallel resonance.

28. What is an electric filter and for what purpose is it used?

PROBLEMS

1. (*a*) What would be the impedance of a circuit of 20 ohms resistance and 10 ohms inductive reactance? (*b*) If a 60-cycle E. M. F. of 110 volts is applied to the above circuit, what current will flow? (*c*) What is the inductance of the circuit? *Ans.* (*a*) 22.3 ohms; (*b*) 4.93 amperes; (*c*) 0.026 henry.

2. (*a*) What would be the impedance of the circuit in Problem 1 if a 50-microfarad condenser were inserted in series? (*b*) How much current would flow? *Ans.* (*a*) 47.42 ohms; (*b*) 2.33 amperes.

3. What E. M. F. must an alternator of 60 cycles supply to a circuit of negligible resistance and having an inductance of 0.2 henry in order that a current of 5 amperes may flow? *Ans.* 376.8 volts.

4. (*a*) Find the current produced by a 25-cycle alternating E. M. F. of 100 volts in a circuit having 25 ohms resistance and 30 microfarads capacitance. (*b*) What is the power factor of the circuit? *Ans.* (*a*) 0.468 ampere; (*b*) 11.7 per cent.

5. Three condensers of 0.5, 1 and 2 microfarads capacitance are connected in series. Determine the total capacitance. *Ans.* 0.286 microfarad.

6. (*a*) What would be the impedance of a circuit consisting of two coils, A and B, and two lamps, all connected in series; coil A has a resistance of 2 ohms and a reactance of 0.5 ohm; coil B has a resistance of 4 ohms and a reactance of 7 ohms; each lamp has a resistance of 50 ohms. (*b*) What would be the impedance of each part of the circuit? *Ans.* (*a*) 106.17 ohms; (*b*) A = 2.06 ohms, B = 8.06 ohms, lamps = 50 ohms each.

7. What would be the impedance of the circuit if the coils and lamps in Problem 6 were connected in parallel? *Ans.* 1.7 ohms.

8. (*a*) What will be the reactance of a coil of wire having a resistance of 4 ohms and an inductance of 0.02 henry, when connected to a 60-cycle alternating E. M. F. of 110 volts? (*b*) What current will flow? (*c*) By what angle will the current lag behind the impressed E. M. F.? (*d*) How many watts will be expended? (*e*) What is the value of the power factor of the circuit? (*f*) If the coil is connected to a direct-current source of 100 volts, how much current will flow? *Ans.* (*a*) 7.54 ohms; (*b*) 12.89 amperes; (*c*) 62°; (*d*) 652.23 watts; (*e*) power factor = 46 per cent; (*f*) 27.5 amperes.

9. The E. M. F. generated in each armature winding of a three-phase alternator is 125 volts, and the current in each is 5 amperes when the machine is connected to a certain load. Determine the voltages between the lines and the current flowing in each line wire when the alternator is Y-connected and when it is Δ-connected. *Ans.* Y, 5 amperes, 216.5 volts; Δ, 8.67 amperes, 125 volts.

10. (*a*) What is the natural frequency of a series circuit having a capacitance of 10 microfarads, and an inductance of 0.352 henry? (*b*) What will be the voltage across the condenser at resonance, when 10 amperes flow through it? *Ans.* (*a*) 85 cycles; (*b*) 1870 volts.

LESSON XXIX

ALTERNATING-CURRENT APPARATUS AND MACHINERY

Transformers — Transformer Regulation and Efficiency — Transformers on Polyphase Circuits — Alternators — Revolving-Armature Alternators — Revolving-Field Alternators — Inductor Alternators — Power Rating of Alternators — Conversion — Rotary Converters — Rectifiers — Questions and Problems.

357. Transformers. — A transformer is a device for transforming electrical energy at one voltage into electrical energy at another voltage, and consists of two electrically-distinct windings which are so arranged that the magnetic flux associated with one winding also threads through the other. When an alternating current is passed through one winding the magnetic flux first rises to full value in one direction, falls to zero, rises again to a maximum value in the opposite direction, and falls again to zero, and so on; this varying magnetic flux induces in the other winding an alternating E. M. F. In the induction coil, ¶ 270, a make-and-break device, or interrupter, was necessarily included in one winding in order to vary the strength of the magnetic field and thus produce an E. M. F. in the other winding, because the induction coil is operated on direct-current circuits. The transformer, however, requires no interrupter, since the change in flux is accomplished by the alternating current itself. The two windings are termed the *primary* and the *secondary*, the primary being the winding which receives the energy from the supply circuit and the secondary that which receives the energy by induction from the primary. In most transformers the two windings are magnetically linked by a closed core of laminated iron.

The construction of transformers for single-phase circuits is shown in Fig. 422; three types are illustrated, namely the core, shell and combined core and shell types. The cores are built up from annealed punchings of thin silicon sheet steel with

the joints staggered so as to yield a core of low reluctance and small iron loss. The two windings are well insulated from each other by a thick shield of layers of mica, or other suitable

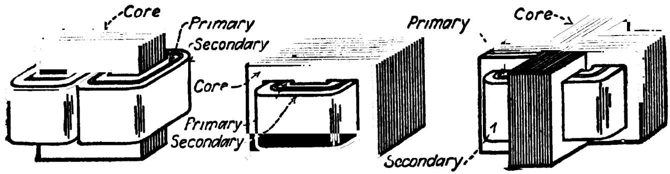


Fig. 422. — Types of Transformers.

Left — core type, center — shell type, right — combined core and shell type.

insulating material, of sufficient size to project beyond the windings. The turns and layers of each winding are insulated from each other by various materials to thicknesses depending on the voltage of the circuit to which they are connected. The windings are usually subjected to a vacuum-drying and filling process which removes all moisture and then impregnates the coils with an insulating compound under pressure. The transformers are placed under oil contained in an iron tank, the oil being used for insulating purposes and for cooling the transformer in order to avoid high temperatures which would injure the transformer insulation. The heat generated in the smaller sizes of transformers is conveyed to the case by the oil and is there dissipated by radiation and natural air circulation. The case for such *self-cooled* transformers is of cast-iron or pressed steel of the form shown in Fig. 423. Such transformers beyond 50 kw. require increased radiating surface, and therefore the tank is universally made in the form of corrugated steel tanks. For the larger sizes external oil-circulating tubes or radiators are used on the tanks, the latter type being shown in Fig. 424. Large transformers may also be cooled by placing coiled pipes in the oil at the top of the transformer tank and pass-

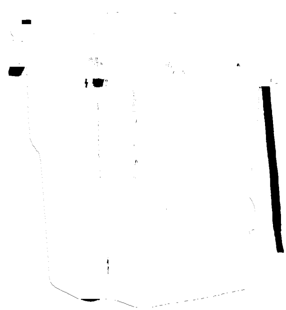


Fig. 423. — Wagner 15-kw. 220-2200-volt Pole-type Distributing Transformer.

ing air or water through these pipes; the latter are called *water-cooled* transformers. Transformers which are not submerged in oil may be cooled by currents of air circulated past the windings and core by means of a blower; these are called *air-blast* transformers.

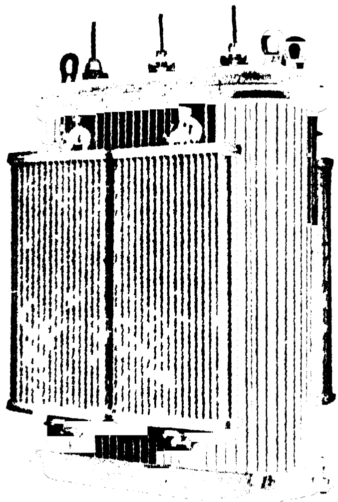


Fig. 124. — General Electric Co., 1000-kw. Self-cooled Transformer.

The function of transformers is to change the voltage from one value to another, this being accomplished by having more turns on one winding than on the other. Thus, if the primary winding has 200 turns and the secondary has 1000 turns, then the voltage available at the secondary terminals will be 1000 ÷ 200 = 5 times as great as the E. M. F. impressed upon the primary. The ratio of the number of turns, n_2, in the high-voltage winding to the number, n_1, in the low-voltage winding is called the *ratio of transformation*, and is given by the equation

$$r = \frac{n_2}{n_1} = \frac{E_2}{E_1}, \quad \ldots \ldots \quad (148).$$

where E_1 and E_2 are the respective voltages of the two windings. When the transformer is used to deliver energy at a higher voltage than that at which energy is received it is called a *step-up* transformer, and when it lowers the voltage it is called a *step-down* transformer. Any desired alternating E. M. F. may be procured by properly proportioning the number of turns on the windings of a transformer.

If there were no losses in a transformer, its power output would be the same as its power input. Since power is equal to volts times amperes (at unity power factor), it follows that

$$P = E_1 \times I_1 = E_2 \times I_2 \quad \ldots \ldots \ldots \quad (149).$$

where I_1 and I_2 are the currents in the low- and high-tension windings respectively. From this equation

$$\frac{E_1}{E_2} = \frac{I_2}{I_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (150).$$

or the ratio of voltages is the inverse ratio of the currents in the two windings. Thus, if 50 amperes traverse the primary winding of the transformer above mentioned, the secondary current would be one-fifth as great or 10 amperes. These values are indicated in Fig. 425. Since all transformers have losses, namely: eddy-current and hysteresis losses in the core and I^2R losses in the primary and secondary windings, equation (150) is not exact, but as the efficiencies of transformers, ¶ 358, are very high—over 95 or even over 98 per cent — this equation may be used for most practical calculations.

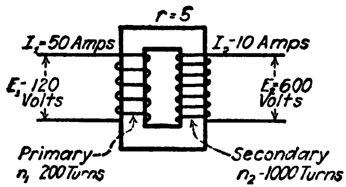


Fig. 425. — Voltage and Current Relations in a Transformer.

Problem 152. — The primary voltage of a 10-kw. transformer used to supply electricity to 110-volt lamps is 2200 volts. What is the ratio of this transformer and what are the full-load currents in the two windings, neglecting losses?

In this step-down transformer which supplies a circuit of unity power factor: $E_1 = 110$ volts, $E_2 = 2200$ volts, and $P = 10{,}000$ watts, therefore from Formula (148)

$$r = \frac{E_2}{E_1} = \frac{2200}{110} = 20,$$

and from Formula (149) $$I_1 = \frac{P}{E_1} = \frac{10{,}000}{110} = 91 \text{ amperes},$$

and $$I_2 = \frac{P}{E_2} = \frac{10{,}000}{2200} = 4.5 \text{ amperes}.$$

Transformers are much used in transmitting and distributing electrical energy over long distances, for efficiency demands high line voltages in order to reduce the line losses, ¶ 325. At the power station the generator voltage is raised by step-up transformers to the value found economical for transmission, and at the receiving substations the line voltage is lowered by step-

down transformers to values suitable to the apparatus supplied with energy, such as motors, rotary converters, lamps, etc.

For some purposes a part of the same electric circuit is used for both primary and secondary windings of the transformer, in which case it is called an *auto-transformer*, Fig. 426. The ratio of transformation is the ratio of the number of turns included between the high-voltage terminals and the number between the low-voltage terminals, Fig. 426. Such transformers are used in starting induction motors, ¶ 370, for compensators for varying the E. M. F. of alternating-current circuits over limited ranges, and for other purposes where small transformation ratios are required.

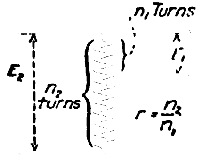


Fig 426 -- Connections of an Auto-transformer.

Another type of transformer which is used in connection with incandescent lighting on series circuits and with electrical measuring instruments is called a *current transformer*. When used for the latter purpose the primary winding is connected in series with the circuit of which the current is to be measured, and the secondary is connected directly with the ammeter terminals. The instrument will then carry a current proportional to but much less than the main current and will not be subjected to the high voltage of the main circuit.

358. Transformer Regulation and Efficiency. In constant-potential transformers the regulation is the ratio of the rise of the secondary terminal voltage from rated load to no load (at the specified power factor and constant impressed primary voltage) to the secondary terminal voltage at rated load. For example, the secondary voltage of a transformer rises from 220 to 230 volts on the removal of rated load; its regulation is $(230-220) \div 220 = 0.045$ or 4.5 per cent.

The primary winding of a transformer possesses a high inductance since it is a coil wound on an iron core. Hence, when an alternating pressure is applied to the primary terminals, a current flows through the primary and produces an alternating magnetic flux in the core; this flux induces a counter E. M. F. in the primary which is nearly equal and in direct opposition to the applied pressure, and with the secondary circuit open only a very small current can flow through the primary. This small current in the primary, however, is sufficient to set up the alternating flux in the

core and induce an E. M. F. in the secondary (¶ 357) in addition to the counter E. M. F. of the primary. This induced E. M. F. in the secondary is in the opposite direction to the E. M. F. applied to the primary and consequently when the secondary circuit is closed by connecting a load to it, a current flows through the secondary in the opposite direction to the current in the primary. The secondary current also tends to produce an alternating flux in the core, which flux is in a direction opposite to that produced by the primary (Lenz's Law, ¶ 261). The effect of the opposing flux set up by the secondary current is to decrease the total flux in the magnetic circuit, which decreases the counter E. M. F induced in the primary, thus permitting a greater primary current to flow. The decrease in magnetic flux and in the primary counter E M. F. in commercial transformers between rated load and no load is very small, since a very small decrease of the primary counter E M F greatly increases the difference between the applied primary pressure and its counter E. M. F. so that the primary current is greatly increased In fact, the increase of primary current due to the loading of the secondary is just great enough (or very nearly) to exactly balance the demagnetizing action of the current in the secondary winding; that is, the flux in the core must be maintained approximately constant by the primary current whatever value the secondary current may have When the load on a transformer is increased, the primary of the transformer automatically takes additional current and power from the line in direct proportion to the load on the secondary.

If the impressed primary voltage is maintained constant, it may be assumed that the secondary voltage of a well-designed transformer will remain practically constant at all loads. There is, however, a slight drop in secondary voltage from no load to rated load, which may vary from 1 per cent to 5 per cent, depending on the design and characteristics of the transformer. The voltage drop varies almost directly as the load, provided the power factor remains constant. On non-inductive load (that is, with a load of 100 per cent power factor) the regulation, as a rule, exceeds the resistance drop by only a small amount. However, with transformers having high reactance this is not the case, since the reactive component of the voltage adds considerably to the resistance drop. On inductive load the regulation depends chiefly upon the reactive drop; hence, the less the reactive drop, the better the regulation and vice versa.

The *efficiency* of a transformer is a ratio of the power output at the secondary terminals to the power input at the primary terminals. To determine the efficiency of a transformer directly by measuring the input and output, does not constitute a satis-

factory method when the efficiency is high. A more accurate method is by measuring separately by a wattmeter, the core and copper losses. The core loss is measured by placing a wattmeter in the primary circuit with the secondary circuit open. The copper loss is measured by placing a wattmeter in the primary circuit and with the secondary short-circuited through an ammeter, applying just enough pressure to the primary to cause the full-load current to flow in the secondary. The losses being known, the efficiency at any load is readily found, bearing in mind, however, that the iron loss is a constant quantity and the copper loss varies as the square of the load. The formula for the efficiency of a transformer is:

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{copper and iron losses}} \quad . \quad . \quad (\mathbf{151}).$$

Problem 153. — If the transformer in Problem 152 has a copper loss of 175 watts and an iron loss of 150 watts when it is delivering its rated output of 10 kw., what is its efficiency?

By Formula (151)

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{10{,}000}{10{,}000 + 175 + 150} = \frac{10{,}000}{10{,}325} = 96.8\%.$$

359. Transformers on Polyphase Circuits. — The connection of transformers to polyphase circuits may be accomplished in many ways, but only a few of the simpler methods will be here considered. Fig. 427 shows the connection diagrams of single-phase transformers applied to two- and three-phase circuits, the ratio of transformation is assumed as 10 and numerical values are assigned to the voltages and currents for illustration. At (a) are shown the connections of two transformers to a four-wire two-phase 1000-volt system in order to transform to a three-wire two-phase circuit. The voltage between the outer low-tension terminals is $100\sqrt{2}$ or 141 volts.

On three-phase circuits either a single three-phase transformer or three single-phase transformers may be used to alter the voltage of the system; the latter plan is assumed in Fig. 427. The three transformers may have their primaries connected to the three-phase supply circuit in Y as shown at (b), or in Δ

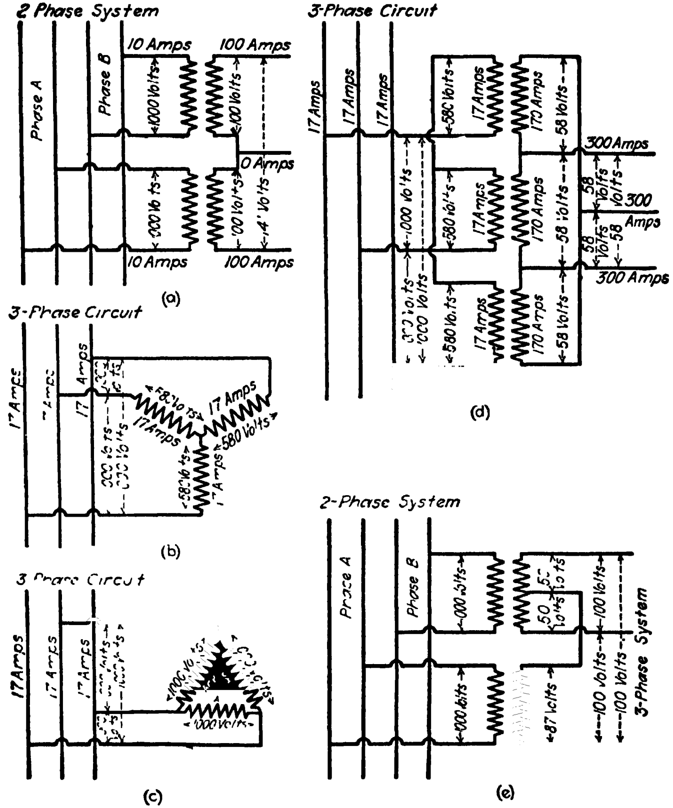


Fig. 427. — Connections of Single-phase Transformers on Two- and Three-phase Circuits.

(a) 4-wire 2-phase to 3-wire 2-phase transformation. (b) 3-phase Y-connection. (c) 3-phase Δ-connection. (d) 3-phase Y- to Δ-transformation. (e) 2-phase to 3-phase Scott transformation

(delta) as shown at (c). If the voltage between any pair of line wires is E volts, then the voltage across each primary is $\frac{E}{\sqrt{3}}$ for the Y-connection and E for the Δ-connection; and if the

current in each line wire is I amperes, then the current in each primary winding is I for the Y-connection and $\frac{I}{\sqrt{3}}$ for the Δ-connection (¶ 353). The primary and secondary windings of the three transformers may both be connected Y, both Δ, or one set of windings Y and the other Δ. At (d) are shown the connections of three single-phase transformers with their primaries connected in Y and their secondaries connected in Δ. A scheme for transformation from a two-phase four-wire system to a three-wire three-phase system is shown at (e); the upper transformer must have a tap at the middle point of its secondary and the lower transformer must have a ratio of 10 to $\frac{1}{2}\sqrt{3}$, or 11.5.

360. Alternators. — Alternating-current generators, or alternators, must, like direct-current generators, have field magnets and an armature; but the commutator of the direct-current machine is replaced by slip rings on the alternator in which the armature or field revolves. The windings of the revolving armature are connected to slip rings, and the alternating E. M. F.'s generated in the windings are delivered to the external circuits by means of the brushes resting on the slip rings. In alternators in which the field revolves, the slip rings carry the direct current, obtained from a separate source, to the field windings.

Alternators may be classified according to construction into three types:

1. Revolving armature and stationary field magnets;
2. Revolving field magnets and stationary armature;
3. Stationary armature, stationary field winding, and a revolving mass of iron termed an inductor; this mass of iron has polar projections that extend radially outward so as to drag the magnetic flux set up by the stationary field winding past the armature conductors.

All alternators must have direct current for field excitation, the direct current being derived from a separate generator termed an "exciter," the machine being used for field excitation only. In some types of alternators, the armature, in addition to the alternating-current winding, has a separate winding

connected to a commutator for producing the direct current for the field excitation, thus making the alternator self-exciting.

The field structure of alternators is multipolar and may consist of as many as 60 or more poles in machines direct-connected to a slow-speed engine; on the other hand, in machines driven by turbines at high speed the number of poles may be very small. The frequency of the E. M. F.'s produced by any alternator, ¶ 328, is obtained by multiplying the number of pairs of poles (half the number of poles) by the number of revolutions per second of the revolving member.



Fig. 428. — Self-exciting Alternator of the Revolving Armature Type.

Alternators may also be classified according to design into:

1. Single-phase alternators.
2. Polyphase alternators.

In a single-phase winding all the inductors are connected in series so that their individual E. M. F.'s will add, the two remaining terminals of the armature winding being connected one to each of two slip rings. The windings on the armature core of a polyphase alternator are separate and distinct for each phase and properly distributed over the armature surface, all the inductors of any one phase usually being in series with each other. A three-phase alternator, for example, delivers three equal and separate E. M. F.'s, which are displaced from each other in time by one-third of a cycle. Fig. 428 shows a three-phase alternator of the revolving armature type; every pair of the three slip rings yield a definite alternating voltage.

361. Revolving-Armature Alternators. The armatures of revolving-armature alternators are similar in construction to those used in direct-current generators but are less complicated because they have fewer coils and do not require commutators with their many connections. The armature cores are

built up from laminations or slotted punchings to form a slotted core, and form-wound coils are placed in the slots. The number of inductors is an even multiple of the number of poles, and the groupings are symmetrical with respect to each pair of poles.

The revolving-armature type of alternator that is self-exciting has two distinct windings on the armature; one winding for generating the alternating E. M. F. and connected to slip rings, and the other winding for furnishing the direct-current for field excitation, this winding being connected to a commutator.



Fig. 429. — Armature of Self-exciting Alternator.

An alternator of this type is shown in Fig. 428 and its armature is depicted in Fig. 429. Alternators of this type are wound for two- or three-phase service; to secure single-phase service from a three-phase alternator the load is connected between any two legs of the three-phase windings. Such alternators when run single-phase yield about 70 per cent of their three-phase capacity.

In Fig. 430 are shown simple diagrams of single-, two- and three-phase windings of a multipolar alternator. In these diagrams the heavy radial lines represent the inductors, and the other lines the connecting wires. Where only one inductor is shown, in practice there would be a number placed in one slot or distributed over several slots. These windings would also apply to the main winding of an armature having an exciter winding.

362. Revolving-Field Alternators. — In generating an E. M. F. there must be a motion of either the inductors or the field magnets, ¶ 275, and it is quite as common in alternators to have the field magnets revolve inside a stationary armature

as to have the armature revolve. Revolving-field alternators, one of which is shown in Fig. 307, Lesson XXIII, have become the recognized standard for alternators of large output, since the stationary armature windings can be more easily insulated to withstand high voltage, and the collection of high-tension

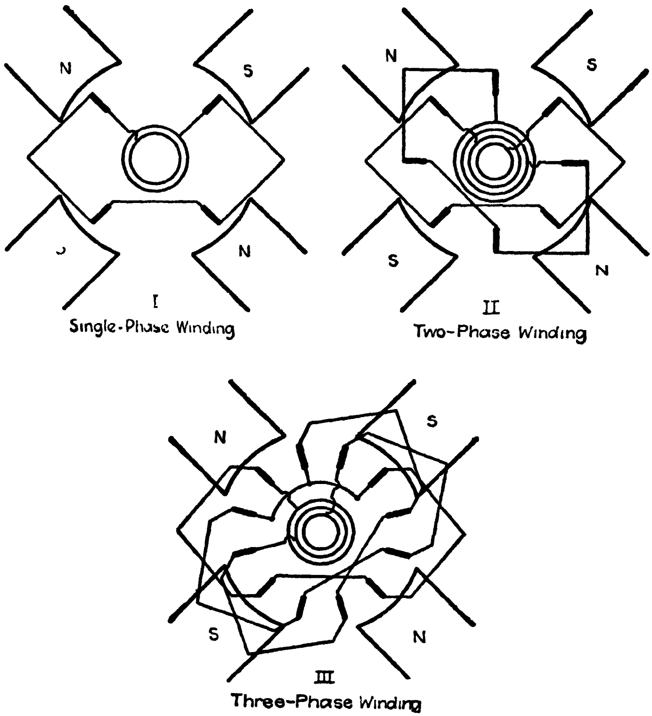


Fig. 430. — Armature Windings of Alternators.

armature currents from the slip rings is avoided. Revolving-field alternators can be constructed to generate 25,000 volts, and machines that are required to give either high voltage or large currents are of the revolving-field type, the revolving-armature type of construction being usually restricted to machines of 25 kw. or less.

The revolving field consists of laminated sheet iron pole pieces bolted to a cast steel or iron ring, which is connected to the hub by spider arms. The pole pieces have a wide face so as to secure not only a wide polar arc for the proper distribution of the magnetic flux, but also to hold the field windings in place, the field winding being wound on spools which are slipped

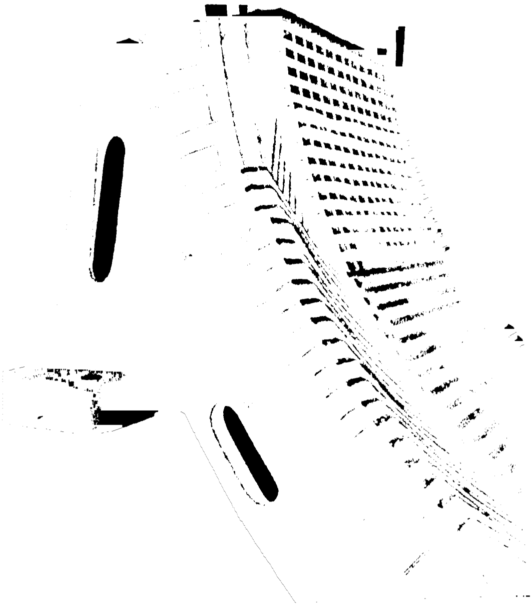


Fig. 431. — Portion of Armature of a Revolving-field Alternator

over the pole pieces before they are bolted to the ring. The low-voltage direct current for field excitation is led to the winding through two collector rings.

The stationary armature consists of a circular cast-iron frame inside of which are dovetailed sheet-iron laminations. The laminations are stacked together and held rigidly in place by steel clamping fingers, ducts being provided at frequent intervals in stacking to allow for the free circulation of air. The

inner surface of the laminations is slotted to receive the windings, consisting of carefully insulated form-wound coils, which are held in the slots by suitable wedges. The method of assembling the armature coils is illustrated in Fig. 431, which shows a portion of a stationary armature. The armature coils are usually connected to furnish two- or three-phase currents.

363. Inductor Alternators. — A modification of the stationary-armature type of alternator is the *inductor* type in which neither the armature nor field windings move, the only moving part being a mass of laminated iron having polar projections.

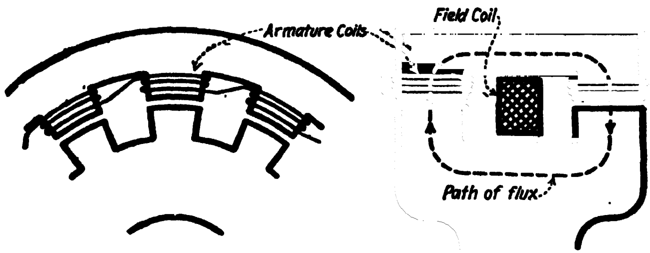


Fig. 432. — Arrangement of Inductor Alternator.

These projections are magnetized by a direct current flowing in a single annular field coil clamped in position in the center of the machine. The schematic arrangement of parts is shown in Fig. 432. The field coil is wound on a copper or brass bobbin, which not only protects it mechanically, but also protects it electrically at such times when the field circuit is broken, as the E. M. F. of self-induction at those instants might be high enough to puncture the insulation. The metallic bobbin acts as a single-turn coil surrounding the decaying magnetic flux, and thus prevents high E. M. F.'s of self-induction in the field winding.

The circular armature frame surrounding the inductor has internal projections forming the cores of the armature coils; their projections are equal in number and size to the inductor projections. The armature coils are form wound and laid in grooves in the armature cores in a manner similar to that of revolving-field machines. The distinguishing characteristic of the

inductor alternator is that any one set of armature coils or portion of armature inductors is subjected to a magnetic flux of one polarity only, the magnetism fluctuating from a minimum to a maximum, the magnetic flux being a maximum through the armature coils when the pole faces of the inductors are directly opposite the faces of the armature poles, and the flux a minimum when the inductors are in an intermediate position. As the inductors revolve, the magnetic flux varies from minimum to maximum and back again but does not reverse its sign since there is only a single field coil.

The advantages claimed for the inductor alternator are absence of any moving wire, thus reducing the danger of chafing the insulation, absence of collector rings and therefore of brush friction, and increased facilities for insulation. These advantages are offset by the fact that only half as great a pressure is obtained by a given flux as would be obtained in the ordinary type of machine, and by the large eddy current loss and bad regulation. This type of alternator has become nearly obsolete, except in special cases, such as high-frequency alternators for radiotelegraphic systems employing undamped waves, ¶ 405.

364. Power Rating of Alternators. — Alternating-current generators are usually rated in kilovolt-amperes (kv-a.) instead of kilowatts, because it would be impossible for the manufacturer to know in advance the amount of inductance and capacitance of the circuits to which the alternator is required to furnish power. The actual energy output in kilowatts is equal to the apparent power or kilovolt-amperes multiplied by the power-factor of the circuit. An alternator having a rating of 100 kv-a. would deliver under full-load conditions 100 kilowatts at unity power factor; but if the power factor should be 0.8 the energy output of the machine would be reduced to 80 kilowatts, for the current and consequently the heating of the armature would be approximately the same as if it were delivering 100 kilowatts at unity power factor.

365. Conversion. — The economical operation of large electrical systems involving the generation, transmission and distribution of large amounts of electrical energy requires that the energy be generated as alternating current in one or more large

central stations. The alternating current is transmitted at high voltage to points where it is to be used, and there stepped down through transformers to suitable commercial voltages. The ease with which the voltage of alternating currents can be changed with transformers has resulted in the almost universal use of such currents in transmission systems. But alternating current cannot be used to perform all the services in which electricity takes part, for example the electrolytic action required in the refining of metals, in electroplating, and in the charging of storage batteries requires direct current. Thus there is frequent need for converting the alternating current into a direct current. The alternating current generated in central stations supplying power to street railway systems, must in many cases, be converted into a direct current, because the railway equipment is of the standard direct-current type so well suited to city traction systems. The future development of the alternating-current series motor, however, will probably reduce this need for current conversion.

The conversion of large amounts of alternating-current power to direct-current power is made by the use of synchronous converters, generally called *rotary converters*, ¶ 366. A converter, in general, is a machine employing mechanical rotation in changing electrical energy from one form into another. In addition to the synchronous converter mentioned above, which may be used to convert from alternating to direct current or vice versa, another form of converter known as a *motor-generator set*, ¶ 375, may perform the same function. The conversion of small amounts of power is considered in ¶ 367.

366. Rotary Converters. — The rotary converter is essentially an alternator and a direct-current generator combined in one machine, the general appearance of which is similar to that of a direct-current generator. It has, in addition, suitable collector rings connected to the armature winding at points having the proper angular relation, the number of rings depending on the number of phases on which the machine is operated.

It was shown in Lesson XXIII that the armature windings of a direct-current generator have an alternating current flowing through them and that, by properly connecting these windings to a commutator, the alternating current is commuted to a

direct current at the brushes. Therefore, if the winding of the revolving armature of an alternator is tapped at the proper points and connected properly to the segments of a commutator a direct current will be delivered to a set of brushes bearing on the commutator. When brushes which rest upon the slip rings are connected with a source of alternating current of proper voltage, the armature will rotate as a motor and the current intake will be sufficient to supply the direct-current circuit and to overcome losses in the converter due to resistance, friction, hysteresis and eddy currents. The windings of a converter armature are closed, like those of a direct-current generator armature, and each slip ring is connected to the armature winding by as many taps as there are pairs of field poles.

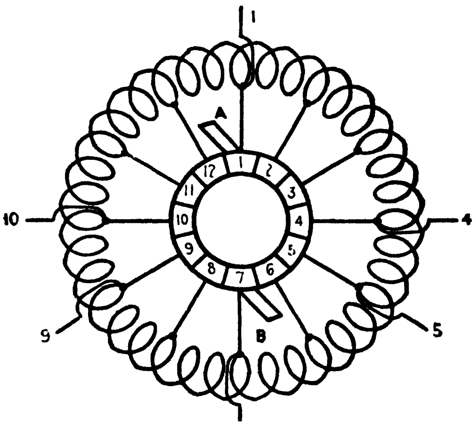


Fig. 433. — Winding of a Rotary Converter Armature for a Bipolar Field.

The taps are shown for single-, two- and three-phase operation

The proper taps for single-, two- or three-phase currents from a ring-wound armature placed in a bipolar field are shown in Fig. 433, the ring-wound armature and the bipolar field being used in order to simplify the explanation. In practice rotary converters have multipolar field frames and drum-wound armatures, but their operation is practically the same as that of the machine represented in Fig. 433.

If the converter represented by the armature in Fig. 433 is to operate on single-phase alternating current, the current is lead to and from the winding through taps 1 and 7, which taps would be connected to two slip rings; for two-phase operation two more rings would be added to the machine and connected to

the taps 4 and 10, thus making four slip rings and four brushes on the alternating-current side of the machine. If the armature were to be used on a three-phase circuit it would be provided with three slip-rings that would connect to the taps 1, 5 and 9 respectively. In any of these cases, whether the machine operates from a single-phase or polyphase circuit, a direct-current pressure can be obtained at the brushes A and B. The continuous E. M. F. bears a fixed ratio to the impressed alternating E. M. F. and will be equal to the maximum alter-

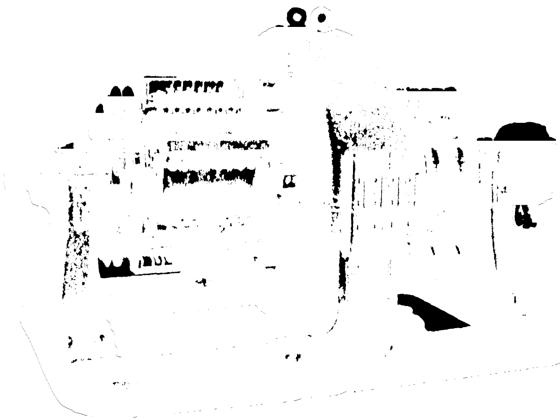


Fig. 434. — Three-phase Synchronous Converter.

nating E. M. F.; therefore, the value of the direct pressure obtained from a single-phase rotary would be equal to the effective value of the impressed alternating E. M. F. times 1.41. For polyphase converters the ratio of conversion will depend upon the number of phases and the method of connecting the windings, for example, in a two-phase rotary the ratio of the alternating to the direct E. M. F. for each phase is 0.71, and in a three-phase rotary this ratio is 0.62 for each phase. Rotary converters are mostly of the polyphase type; a three-phase rotary is shown in Fig. 434.

Rotary converters may be started and be brought up to synchronous speed by the same methods that are employed

with synchronous motors, ¶ 374. They may also be started from the direct-current side when direct current is available, by operating the machine as a direct-current shunt motor and, after shutting off the direct-current, applying the alternating current through the low-voltage taps of an auto-transformer, the voltage being increased until the machine is in synchronism. If a direct current is supplied to a rotary converter through the brushes and commutator it will run as a shunt motor while alternating current may be taken from the slip rings· under these conditions the machine is termed an *inverted converter*.

Rotary converters of large capacity or those that may be required to carry large momentary overloads have commutating poles, which fulfill the same functions as they do in direct-current generators and motors, ¶ 296, that is, insuring sparkless commutation from no load to heavy loads with a fixed brush position. Machines of this type that are started from the alternating-current side are provided with a mechanical brush-raising device, for the brushes must be raised from the commutator in order to prevent sparking. Another use that is made of the commutating poles in rotary converters is to provide regulation of the ratio between the voltages of the direct-current side and the alternating-current side by varying the excitation of the commutating poles with a field rheostat that is inserted in series with the pole windings; converters having this form of regulation are termed *regulating-pole* rotary converters.

Regulation of the voltage of converters is also accomplished by means of reactors connected in the leads to the slip rings of the machines. The field excitation is adjusted so that the converter takes a lagging current at light load, and a leading current at heavy load. This phase shift causes the converter alternating voltage, and likewise the continuous voltage, to increase automatically as the load on the machine increases.

The synchronous booster converter consists of the ordinary converter mounted on the same shaft with an alternator having the same number of poles, the armature windings of the alternator being included in the taps to the slip rings. By varying and reversing the field excitation of the alternator, the alternating voltage impressed upon the converter element can be

increased or decreased as desired, and the direct-current voltage controlled accordingly; the latter voltage is usually varied from

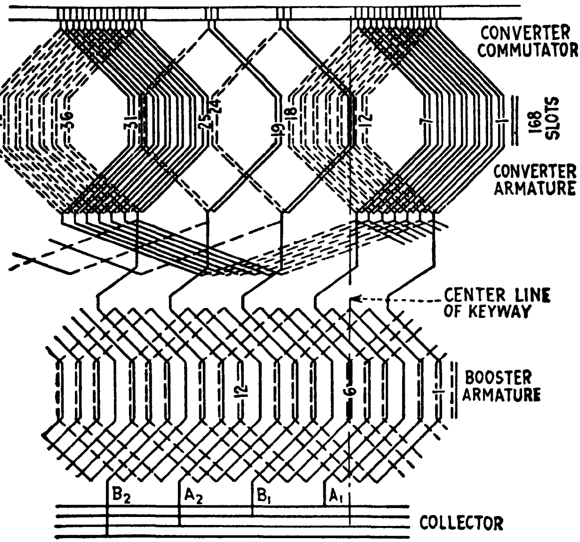


Fig. 435. — Connections of a Synchronous Booster Converter.

15 to 30 per cent above and below normal. Fig. 435 illustrates the connections of such a machine.

367. Rectifiers. – To change small amounts of alternating current to direct current, a cheaper device than the rotary converter or motor-generator set is used, and is termed a *rectifier*. There are four types in use, namely: the mercury arc rectifier, the vibrating rectifier, the tungar rectifier and an electrolytic rectifier.

Mercury Arc Rectifier. — The essential part of the mercury arc rectifier is a glass bulb of the shape shown in Fig. 436, exhausted of air and containing only mercury vapor. The tube has four terminals passing through the glass and connecting with iron or graphite electrodes, the two lower electrodes 1 and 4 being covered by pools of mercury. This device is a valve in that it permits current to flow only from a positive

terminal *to* the pool of mercury; thus current may flow from either electrodes 2 or 3 to the mercury pool 1, but not in the reverse direction. A bulb of this nature would cease to operate on alternating-current voltage after half a cycle if some means were not provided to maintain a flow continuously toward the negative electrode. The two anodes, 2 and 3, connected to each side of the transfo.mer are also connected through reactances L and L_1 to one side of the battery B, and the cathode, 1, is connected to the other side of the battery. The small starting electrode, 4, is connected through a resistance to one side of the alternating-current circuit, and, by tilting the tube so the mercury bridges the space between electrodes 1 and 4, an arc forms as the tube is brought back to its vertical working position, thus starting the operation of the rectifier bulb. If at that instant the terminal T of the transformer is positive, the anode 2 will be positive, and the current will pass from 2 to 1, then down through battery B, through reactance coil L and back to the negative terminal T_1 of the transformer, as shown by arrows not inclosed in circles. When the alternating E. M. F. falls, before it reaches a value insufficient to maintain the arc, the reactance L comes into play and keeps the current flowing for a short time in the same direction as formerly.

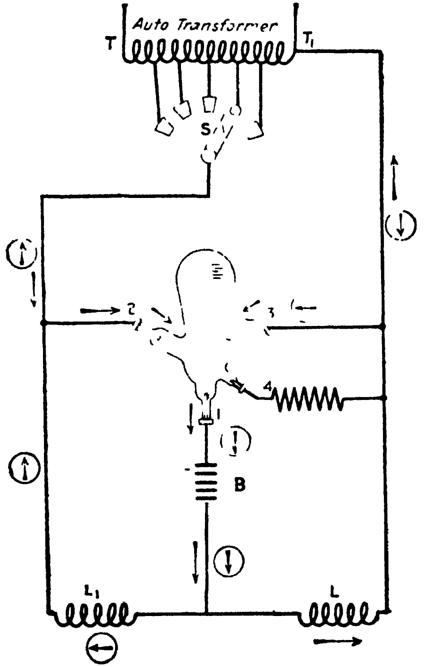


Fig. 436. – Mercury Arc Rectifier.

This serves to maintain the arc in the rectifier bulb until the voltage of the alternating-current supply has passed through zero, reverses and builds up such a value as to cause the anode 3 to have a sufficiently positive value to start the arc between it and the cathode 1. The discharge circuit of the reactance L in the meanwhile is through the arc between 3 and 1 instead of through its former circuit, and the direct current down through the battery continues. The arc between 3 and 1 is later supplied with current from the transformer since terminal T_1 is then positive; the circuit is indicated by the arrows inclosed in circles.

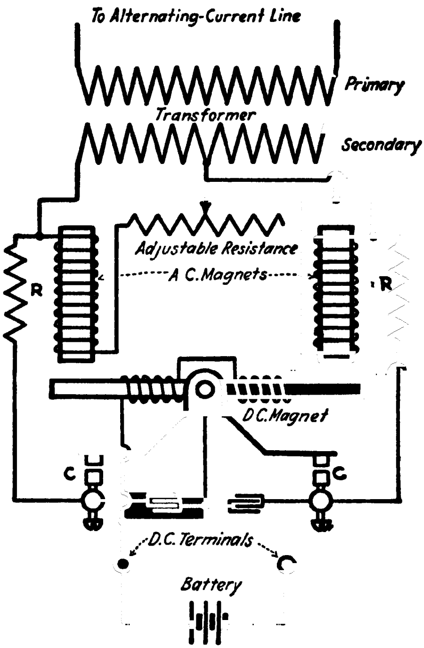


Fig. 437. — Circuits of a Vibrating Rectifier.

To obtain the correct voltage for the battery B which is being charged, the auto-transformer from which current is derived is tapped at the proper point by the aid of a dial switch, S. The ordinary form of this type of rectifier used for charging vehicle batteries has a maximum capacity of 30 amperes.

Vibrating Rectifier. — The vibrating rectifier is a mechanical device for changing an alternating current to a direct current. Its chief use is for charging three-cell storage batteries, such as are used on automobiles or for gas engine ignition, from an alternating-current lighting circuit. The rectifier consists of a transformer to reduce the voltage of the lighting circuit to the

proper value, and an electrically-operated switching mechanism to rectify this reduced voltage. In this rectifier, the circuits of which are shown in Fig. 437, the transformer is used, not only to reduce the voltage, but also to provide a neutral or return path for the direct current. The load current flows from one end of the secondary winding of the transformer, through the regulating resistance, R, through one pair of contacts, C, which are automatically closed at the proper time, and out from the center point of the vibrating armature to the battery under charge, from which it returns to the central point, or neutral, of the transformer. During the succeeding half cycle, when the voltage of the transformer secondary is reversed in direction, the other pair of contacts is closed and voltage is applied to the battery from the half of the secondary previously idle this voltage being in the same direction as during the preceding half cycle. The important part of the rectifier, and upon which its successful operation depends, is the vibrating mechanism which reverses the connections in synchronism and in step with the reversal of voltage so as to open the current-carrying circuit at the instant of zero current and thus prevent sparking and injurious wear of the contacts. The vibrating part of the apparatus consists essentially of a polarized relay acted upon by two alternating-current magnets so that it vibrates in synchronism with the alternations of the current. The vibrating arm is magnetized by a current shunted from the battery, so that one end is permanently north and the other end permanently south, depending on which way the battery is connected. The two alternating-current magnets are stationary and wound so that their lower ends are of the same polarity at each instant. When the alternating current flows in one direction, the lower poles of both stationary magnets will be *north*, consequently attracting the *south* end of the vibrating arm and repelling the north end, which causes one set of contacts to close. As the current reverses both lower poles of the magnets will become *south*, thus attracting the *north* end of the vibrating arm and closing the other set of contacts.

The Tungar Rectifier. — A vacuum tube containing a hot and a cold electrode acts as a rectifier, ¶ 384, and this principle is utilized in the Tungar bulb, Fig. 438. The bulb con-

tains an inert gas at low pressure, a filament of small tungsten wire coiled into a closely wound spiral, and a piece of graphite of relatively large area, the graphite serving as the anode and the tungsten filament as the cathode. The inert gas in the bulb is ionized by the negative charges of electricity or *electrons* which are emitted from the incandescent filament, and the ionized gas acts as the principal current carrier and is capable of passing a current of several amperes, the current being limited by the design and size of the bulb. During one half cycle, when the incandescent tungsten filament is negative, the electrons emitted from it are being attracted toward the anode by the voltage across the bulb, these electrons colliding with the gas molecules and ionizing them, that is, making them conductive in the direction of anode to cathode; while during the other half cycle, when the filament is positive, any electrons that are emitted are driven back to the filament, so that the gas is non-conductive during that half cycle; consequently the bulb rectifies only one half the alternating-current wave.

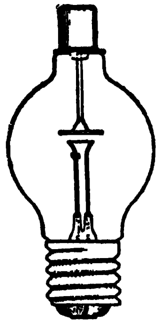


Fig 438. — Tungar Bulb

The connections of a half-wave Tungar rectifier are shown in Fig. 439, the apparatus consisting of the bulb B, with filament (cathode) C and anode A, the transformer T for furnishing current to the filament, the rheostat R, and the storage battery. Assuming an instant when terminal 1 of the alternating-current supply is positive, the current flows in the direction of the arrows through the battery, rheostat, bulb and back to the opposite terminal 2 of the alternating-current line. When terminal 2 becomes positive no current flow takes place, for the current is permitted to flow only from the anode to the cathode, or against the flow of emitted electrons from the cathode,

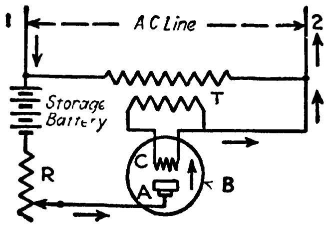


Fig 439 — Circuit of Half-wave Tungar Rectifier.

but it cannot flow from the cathode to the anode. To rectify both half-waves would require two bulbs properly connected. The general principles just described apply equally well to the half-wave and full-wave types of rectifiers. The half-wave rectifiers are particularly applicable to low-current, low-wattage designs, on account of the much lower cost of manufacture and lower cost of bulb renewals.

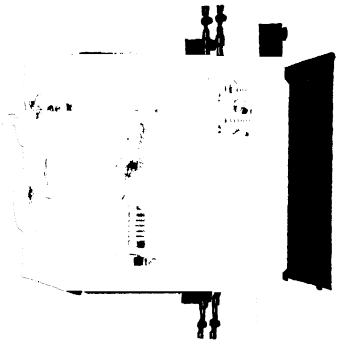


Fig. 440. — General Electric Co. Tungar Rectifier.
Six-ampere 75 volt size

Commercial types of this form of rectifier, one type of which is shown in Fig. 440, are made in the following sizes for operation on 115-volt, 60-cycle alternating-current circuits: a 2-ampere, 7.5-volt unit for charging small three-cell batteries at 2 amperes; a 6-ampere, 7.5 15-volt unit, for charging three or six cells of battery at 6 amperes; a 6-ampere, 7.5–75-volt unit for charging from three to thirty cells of battery at from 1 to 6 amperes.

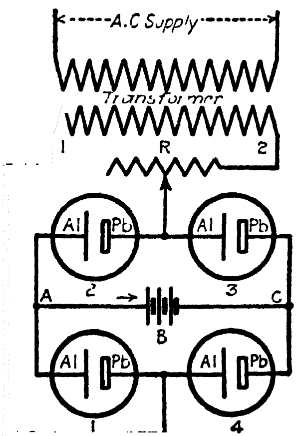


Fig. 441. — Connections of a 4-cell Electrolytic Rectifier.

Electrolytic Rectifier. — To obtain relatively small amounts of direct-current power from alternating-current circuits, use is made of the fact that certain metals when immersed in certain electrolytes offer a high resistance to the passage of an electric current in one direction and a low resistance if the current flows in the other direction. For commercial use a cell consisting of a plate of aluminum and a plate of lead immersed in a solution of am-

monium phosphate has been found to give the best results. The action when alternating current is sent through the cell is the formation of a film of hydroxide of aluminum over the surface of the aluminum plate, which offers a high resistance to the current when it flows from the aluminum to the lead through the solution, but offers very little resistance when flowing in the opposite direction, resulting in a suppression of half of the alternating wave, and producing pulsating current in one direction only.

Both halves of the alternating waves are utilized by an arrangement of four cells connected as in Fig. 441. A transformer is generally used as shown to reduce the line voltage to the lower voltages needed for battery charging purposes and the exact amount of resistance is regulated by the resistance R. The current will flow during one alternation from terminal 1 of the transformer through cell 1, battery B to point C and then through cell 3, to terminal 2 of the transformer; during the next alternation the current will flow from terminal 2 through cell 2, battery B to point C and then through cell 4 to terminal 1. It will be noted that the current always flows through the cells from the lead plate to the aluminum plate, as very little current can flow from the aluminum plate to the lead; therefore, the current always flows from point A and it is to this point that the positive terminal of the storage battery must be connected to have the charging current flow through the battery in the proper direction. To obtain the best efficiency with the above apparatus the electrolyte should be kept at a temperature not exceeding 70° Fahrenheit.

QUESTIONS

1. What is the function of a transformer and what does it consist of?

2. Name three types of transformer construction and give several methods used for cooling transformers.

3. Describe the action of a transformer with a load on the secondary.

4. How would you determine the efficiency of a transformer?

5. What are the two general types of construction used for alternators?

6. What are the advantages of a revolving-field alternator over one of the revolving-armature type?

7. Is the three-phase alternator armature of Fig. 430 Δ- or Y-connected?

8. What are rotary converters and for what purpose are they used?

9. What is the difference between a rotary converter and a motor-generator set?

10. What is a rectifier, name four different types?

11. Make a sketch of the mercury arc rectifier circuits and describe the action of this type of rectifier.

12. Describe the Tungar rectifier.

PROBLEMS

1. What is the frequency of an alternator having 30 poles and revolving at 240 revolutions per minute? *Ans.* 60 cycles.

2. What are the full-load currents in the two windings of a 20-kw. transformer that is used to supply electricity to a number of 110-volt lamps? The primary voltage is 2200 volts, ratio of the transformation is 20, and the efficiency of the transformer is 97 per cent. *Ans.* 9.09 amperes in primary; 181.8 amperes in secondary.

3. (*a*) The copper and iron losses of a 25-kw. transformer are 400 watts and 350 watts respectively when the transformer is delivering full load; what is its efficiency? (*b*) If the secondary voltage at full non-inductive load is 112 volts, what should be the voltage at the primary if the ratio of transformation is 10? *Ans.* (*a*) 97 per cent. (*b*) 1156 volts.

4. Electrical energy of 1100 kw. is to be delivered at 2200 volts from secondaries of transformers located in a sub-station situated 25 miles from a hydro-electric generating plant. Efficiency of the step-down transformers in the sub-station is 98 per cent, ratio of transformation is 10. (*a*) What is the voltage at the primaries of the step-down transformers? (*b*) What is the voltage at the secondaries of the transformers located in the generating station if there is a voltage drop of 10 per cent on the transmission line? (*c*) What power is delivered to the secondaries of the transformers in the generating station? (*d*) What would be the circular mil area of the wire required to effect the transmission? *Ans.* (*a*) 22,450 volts; (*b*) 24,950 volts; (*c*) 1248 kw.; (*d*) 57,000 circular mils.

LESSON XXX

ALTERNATING-CURRENT MOTORS

Polyphase Induction Motors — Squirrel-Cage and Wound Rotor Induction Motors — Starting of Polyphase Induction Motors and Speed Control — Single-Phase Induction Motors—Single-Phase Commutator Motors — Synchronous Motors — Starting of Synchronous Motors — Motor-Generator Sets — Questions.

368. Polyphase Induction Motors. — There are four general types of alternating-current motors:

1. Polyphase induction motors,
2. Single-phase induction motors,
3. Single-phase commutator repulsion motors,
4. Synchronous motors.

The polyphase induction motors of the squirrel-cage armature type is the simplest and most common form for industrial use. The induction motor may be compared with a direct-current shunt motor in that it has two parts: the stationary part corresponding to the direct-current motor field is called the *stator* and the rotating member that corresponds to the armature of the direct-current motor is called the *rotor*, the essential difference being that the armature or working current of the direct-current motor is led into it by brushes, while the working current of the induction motor is an induced or " transformer " current in the rotor windings produced by the alternating field set up by the currents flowing in the stator windings. The induction motor thus combines the principles of a motor and a transformer, rotation being produced by the revolving member following a *rotating magnetic field*, which is the resultant of two or more alternating magnetic fields set up by the polyphase currents flowing through the stator windings. The speed of rotation of the field is given

by the following equation which is derived from Formula (117) by transposition

$$\text{rev. per min.} = \frac{120 \times \text{frequency}}{\text{number of poles}}; \quad . \quad . \quad . \quad . \quad \textbf{(152)}.$$

this is known as the *synchronous speed* of the induction motor.

As a simple illustration of the principle of a rotating magnetic field, imagine a horseshoe magnet to be held over a compass The needle will immediately take up a position parallel to the magnetic flux passing from one pole of the magnet to the other, and it is perfectly obvious that if the magnet is rotated the compass needle will follow. A rotating magnetic field can also be produced by polyphase currents flowing through two or more groups of coils wound on inwardly projecting poles of a circular iron ring, the coils on each group of poles being wound alternately in opposite directions and connected to a single E. M. F. This action will be explained by the aid of Fig. 442, which shows a four-pole field ring energized by two windings connected separately with the two phases of an alternator. The direction of the magnetic field will be indicated by a magnetic needle which will always move to a position where it will be parallel with the magnetic flux passing from pole to pole. If the current in one set of coils is increasing while the current in the other set of coils is decreasing, the needle will be attracted toward the poles in whose coils the current is increasing until that current reaches its maximum value. At the bottom of Fig. 442 is shown the phase relation of the two sinusoidal E. M. F.'s which are applied to the two windings of the four-pole ring, phase 1 supplying current to the coils on poles A and A_1 and phase 2 supplying current to the coils on poles B and B_1.

In Fig. 442, at I, the current of phase 1 is at a maximum and the poles of coils AA_1 are fully magnetized, while the poles of BB_1 are not magnetized since the current of phase 2 is zero at the instant shown; consequently the magnetic needle (or a bar of iron may be used) will assume the vertical position shown. At the instant shown at II, the current in coils AA_1 (phase 1) has decreased to the same value as that to which the current in coils BB_1 (phase 2) has increased and the four poles

are now equally magnetized as shown, drawing the needle to the position indicated. At the instant shown at III, the current of phase 1, connected to coils AA_1, has decreased to zero,

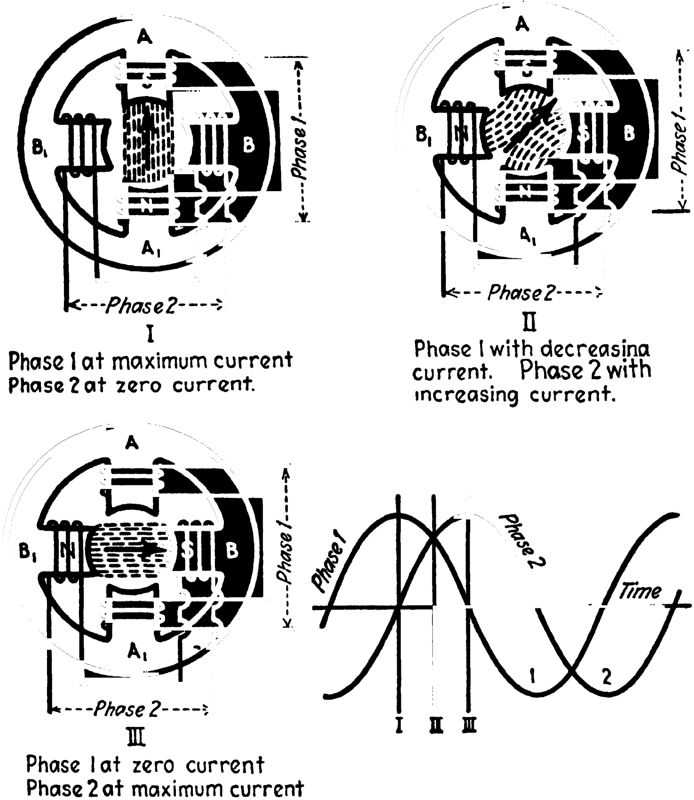


Fig. 442. — Production of a Rotating Magnetic Field by Two-phase Currents.

while the current of phase 2, connected to coils BB_1, has reached a maximum. The magnetism of coils BB_1 draws the needle into a horizontal position. The above action is repeated during successive instants of the flow of the alternating currents and

the needle continues to revolve in the same direction within the field frame as long as the two-phase currents are supplied to the two sets of coils. If the compass needle be replaced by an iron core wound with copper conductors, secondary currents will be induced in these conductors producing a magnetic field which will react on the rotating magnetic field and cause rotation of the iron core (the rotor), just as the compass needle of Fig. 442 revolved with the rotating field. The rotating magnetic field exerts a pull or drag upon the rotor which causes it to revolve with the field.



Fig 443. — Stator of Polyphase Induction Motor.

The torque exerted by the rotor in a field frame constructed with projecting poles, as in Fig. 442, would not be uniform, as the magnetic flux from instant to instant in such a field would be irregular and the attraction or drag on the rotor pulsating in effect. Commercial polyphase induction motors have multipolar field frames without such projecting poles. The laminated core of the stator of induction motors is built up of thin iron or steel plates having slots in which the windings are imbedded, the stator, Fig. 443, resembling the stationary armature of a revolving-field alternator. The coils of the stator winding are distributed symmetrically over the entire face of the core and connected to form distinct groups which overlap each other. The windings are formed into two circuits for a two-phase motor and into three circuits for a three-phase motor, and these circuits are supplied with current respectively from a two- or three-phase alternator.

Fig. 444 shows diagrammatically the arrangement of a two-phase stator, in which the A coils connect to one phase and the B coils to the other phase of a two-phase circuit. Starting

with instant I when the current in coils A is at its maximum value, and consequently the magnetizing force of this set of coils at its maximum, the current and magnetizing force of circuit B will be at zero value. Four poles, alternating **N** and **S** around the core, are formed directly under coils A. As the current in circuit A begins to decrease, that in B rises, and the magnetizing forces of the two overlapping windings will act together at some points and are opposed at others, making the resultant magnetic field shift to one side of the former position. As the current in circuit A gradually falls to zero and that in circuit B rises to its maximum value the magnetic field shifts around

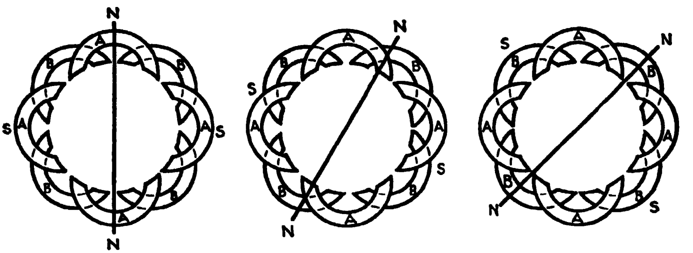


Fig 444. — Progressively Shifting Magnetic Field Produced in a Multipolar Field Ring with Two-phase Currents.

until it is directly under coils B. If the current in circuit A should next increase in the same direction as before, while that in circuit B diminished, the magnetic poles would shift back again to their former position. But after reaching zero value, the current in circuit A rises in the opposite direction, while that in B falls. This shifts the resultant poles forward instead of backward, and they gradually shift ahead until they are again directly under coils A. But the **N** poles now occupy the former position of the **S** poles. Thus, with the current in circuit A passing from a maximum in one direction to a maximum in the opposite direction, the poles have shifted forward the width of one polar space. Current in circuit B next rises in a reversed direction and the poles shift forward until, when the current in B is a maximum, they are under coils B. The diagrams I, II, III of Fig. 444 show the positions of the shift-

ing field under certain conditions of current in the two circuits. In II the position shown is an arbitrary one, for it depends upon the relative values of the currents in the two circuits. With the two currents equal, the position of the line N-N would be halfway between coils A and B.

369. Squirrel-Cage and Wound Rotor Induction Motors. *Squirrel-Cage Rotors.* — The rotor or armature of a squirrel-cage type induction motor is shown in Fig. 445, and consists of a laminated steel core having slots that are parallel with the rotor axis in which copper bars are imbedded. The bars are connected in parallel to copper collars placed one at each end of the rotor; these are termed *end rings*. The current induced in the copper conductors flows in a direction parallel with the rotor axis and the reaction of the magnetic flux of these rotor conductors against the rotating field is therefore in a proper direction to produce rotation. The speed at which the rotor revolves is always less than that of the revolving field, for if the rotor revolved at the same speed as the rotating field there would be no cutting of the rotor conductors by the field, hence no induced current in the rotor conductors nor reactions on the rotating field to produce mechanical power by the rotor. The ratio of the difference in speed of the rotor and the rotating field to the speed of the rotating field is known as the "*slip*" and is usually expressed as a percentage. As the load on the motor is increased the speed of the rotor decreases almost in proportion to the load over a certain range; the maximum speed would then occur when the motor is running with no load.

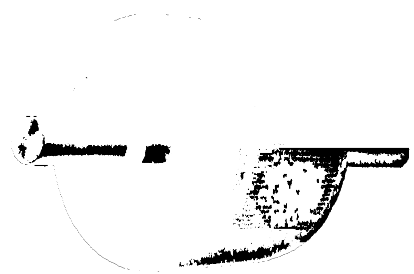


Fig. 445. — Rotor of Squirrel-cage Motor.

The polyphase induction motor with squirrel-cage rotor has the advantages of being simple and rugged in construction, self-starting under load, exerting a powerful torque, and having a practically constant speed at all loads. This type of

motor is particularly suitable in places where there is inflammable material, as the motor requires no collector rings and brushes from which sparks are liable to arise. Fig. 446 shows an assembled polyphase induction motor.



Fig. 446. — Squirrel-cage Induction Motor Complete.

In order to reverse the direction of rotation of a polyphase induction motor it is necessary to reverse the direction of rotation of the field, which is accomplished by reversing the flow of current in only one of the phases. By referring to Fig. 442, it can be seen that if the connections to one of the phases had been reversed the field would have revolved in the opposite direction.

Wound Rotors. — A type of rotor frequently used in large induction motors has polar windings similar to the winding on the stator. In one type the rotor windings are short-circuited

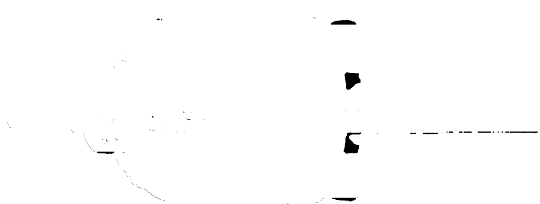


Fig. 447. — Wound Rotor of Induction Motor.

through an adjustable resistance carried on the rotor spider, the resistance being gradually cut out of circuit as the motor speeds up by pushing a knob on the end of rotor shaft; the motor at full speed operates as a squirrel-cage motor, with short-circuited winding. The maximum torque which an induction motor can exert is found to be the same for different rotor

resistances, but the speeds when exerting this maximum torque are different. A high rotor resistance means that the torque will be large at low speeds and that the current will be relatively small. Therefore resistance is inserted in the rotor winding at starting of the motor in order to insure a small starting current under load and a high starting torque.

In another type of wound rotor, Fig. 447, the winding terminals are brought out to slip rings, and the starting resistance, which is external to the motor, is connected with the rotor windings by means of brushes rubbing upon the slip rings. When the motor reaches its proper speed, the resistance is gradually cut out so that a large torque is secured within the operating speed range.

370. Starting of Polyphase Induction Motors and Speed Control. — If the stator windings of an induction motor, whose rotor is at rest, be connected directly to the supply circuit they would draw large currents, for exactly the same condition arises as when the primary of a transformer, whose secondary is short-circuited, is connected directly to the supply circuit. These starting currents in the induction motor become less as the rotor acquires speed.

Induction motors of small size may be connected directly to the supply line through fuses and a switch, but the momentary rush of current at the start may be five to eight times that of the full-load current and consequently a fuse that would protect a motor from an injurious overload might be blown whenever the motor is started. This condition can be met by a special arrangement of fuses for motors which are not equipped with a starting device. This arrangement employs two sets of fuses, one set having a current-carrying capacity that would accommodate the starting current without blowing, and the other set of fuses having a lower capacity sufficient to carry the full-load current of the motor; in case of an overload on the motor the latter fuses will be blown and protect the motor. Such an arrangement of fuses and a double-throw switch is shown in Fig. 448. The switch is thrown down to start the motor, thus connecting it directly to the line through the starting fuses, then, when the motor has gained nearly full speed, the switch is quickly thrown up, thus putting the run-

ning fuses in series with the motor. Automatic starters may also be used with small motors; they consist of double-pole switches which are magnetically operated.

The method of starting squirrel-cage induction motors having outputs say of 50 H. P. and over is to reduce the voltage applied to the motor at starting; the voltage is reduced through an auto-transformer termed a *starting compensator* or *auto-starter*. The auto-starter first connects the motor to the line through the auto-transformer so that the voltage is reduced and the current drawn from the line kept within moderate limits; naturally the starting torque is also reduced. After the rotor has increased sufficiently in speed the motor terminals are connected directly across the line. An internal view of a Westinghouse auto-starter is shown in Fig. 449. The switch is operated by the handle at the right, and the mechanism is such that the handle must be moved to the starting position before it can be moved to the running position, thus insuring proper operation.

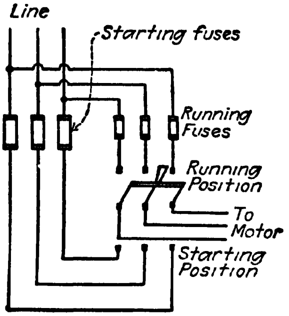


Fig. 448. — Connections of Two Sets of Fuses for Starting Small Induction Motors.

A connection diagram of the Westinghouse starter appears in Fig. 450. It has two auto-transformers T connected in open Δ, and both ends of the transformers are disconnected from the line when the starter is placed in the "off" position. In the starting position switches A are closed to impress 65 or 80 per cent of full voltage on the motor, and in the running or full-voltage position only switches B are closed, thereby removing the compensators from the

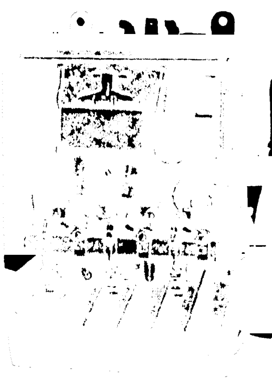


Fig. 449. — Auto-starter.

circuit. The starter is also equipped with the overload coils O and overload trip C, and the low-voltage release coil L.

The auto-transformers of motor starters are designed for much higher current and magnetic densities than are ordinary transformers because of the short time that they are in service. Although only one tap is used, the auto-transformer is usually provided with three taps to meet different starting conditions. If, for example, the starting current taken by a motor at full voltage is 500 per cent of normal, then on the 65 per cent tap the current would be 210 per cent of normal

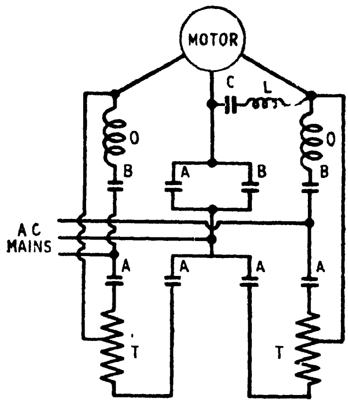


Fig 450 – Connections of a Three-phase Auto-starter.

Another method of starting induction motors is by inserting resistance in the rotor circuit, this method being applicable naturally only to motors having wound rotors. This resistance may be mounted directly on the shaft inside the rotor and controlled by a switch on the rotor shaft, as explained in ¶ 369. With the slip-ring type of induction motor having a wound rotor, the starting resistance is external to the motor and in the form of a "starting box," somewhat similar to that for a direct-current motor, there being a variable non-inductive resistance coil for each rotor circuit. Fig. 451 shows the internal connections of a rheostat for a three-phase slip-ring motor, the resistance coils for the three phases being simultaneously controlled by the three rheostat arms which are rigidly connected together. To start the motor the stator windings are connected to a three-phase supply circuit and the rheostat handle is moved in a direction to decrease the resistance in the three rotor circuits; when the rheostat arms have been moved to the limit of their motion all resistance has been cut out and the rotor winding short-circuited, the motor having reached its full speed.

The foregoing method of varying the amount of resistance in the rotor circuit is also used when it is desired to vary the speed of an induction motor over a small range; if the resistance of the rotor circuit is increased the rotor current is decreased and the speed drops in order that the former rotor current value may be restored, resulting in inefficient operation of the motor. The speed of an induction motor can also be varied by altering the voltage applied to the stator windings, or altering the number of rotating poles by commutating the stator windings. If the voltage applied to the stator is reduced the capacity of the motor is reduced since the capacity varies as the square of the impressed voltage. Altering the number of rotating poles requires an external switching device by means of which the polar grouping can be readily changed to give the desired synchronous speeds; such a motor is called a *multi-speed* induction motor. Among the other schemes of speed control used are: cascade control, dynamic control, and brush-shifting motors.

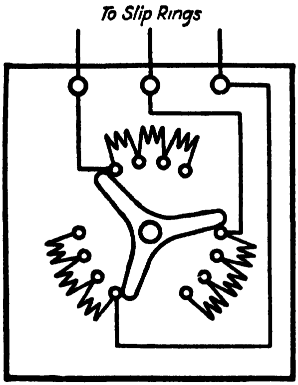


Fig. 451. — Starting Resistance for a Three-phase Slip-ring Induction Motor.

371. Single-Phase Induction Motors. — The single-phase induction motor differs from the polyphase type principally in the character of its magnetic field, as an ordinary single-phase winding will not produce a rotating field, but a field that is oscillating, and the induced currents and poles produced in the rotor by this field will tend to produce equal torque in opposite directions, therefore, the rotor cannot start to revolve. However, if the rotor can in some manner be made to rotate at a speed corresponding to the frequency of the current in the stator windings, see Formula 152, ¶ 368, then the reaction of the stator and rotor flux is such as to produce a torque that will keep the rotor revolving.

In practice the starting of single-phase induction motors is

accomplished by three general methods applicable to small-sized motors only. First: the split-phase method, in which an auxiliary stator winding is provided for starting purposes only, this winding being displaced from the main stator winding by 90 electrical degrees. It has a higher inductance than the main stator winding, thus causing the current in it to lag far enough behind the current in the main winding to produce a shifting or rotating field during the starting period, which exerts a starting torque on the rotor sufficient to cause rotation. When nearly normal speed has been reached the auxiliary winding is cut out of circuit by a switch and clutch in the motor, which operates automatically by centrifugal force, and the motor continues to run as a single-phase motor. The starting torque of such motors being limited, they are frequently constructed with the rotor arranged to revolve freely on the shaft at starting until nearly normal speed is reached, at which time the load is picked up by the automatic action of a centrifugal clutch.

Second: an auxiliary winding may be connected to the single-phase line through an external inductance and a switch (for disconnecting the auxiliary winding from the circuit after the motor has reached normal speed), the introduction of the inductance in the auxiliary winding splitting the phase as before.

An ordinary polyphase induction motor may be operated on a single-phase circuit by splitting the single-phase in a manner similar to the above. If a two-phase motor has its two stator windings connected in parallel to a single-phase line but with as much reactance as possible in series with one of the stator windings, while resistance is placed in series with the other, the current in one winding will be considerably out of phase with the current in the other, and a non-uniform rotating field will be produced. The squirrel-cage rotor will revolve in such a field but it will not develop the same amount of power as with a perfect rotating field.

One of the stator windings may be disconnected from the circuit after the motor has attained normal speed, the motor then operating as a single-phase motor. Single-phase motors operated on the above principle are manufactured by the General Electric Company; the stator of this type of motor has symmetrical three-phase windings which may readily be re-

connected for operations on three-phase circuits. When operated on a single-phase circuit, the stator windings are connected to it through a resistance and reactance at starting by means of a starting box similar in appearance to the direct-current motor starting box. The rotor in this type of motor revolves freely on the shaft until about 75 per cent of normal speed is reached when the load is picked up by the action of a centrifugal clutch.

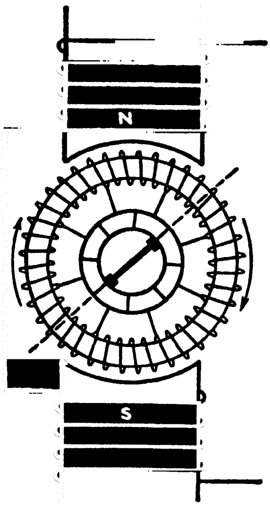


Fig. 452 — Diagram of Two-pole Repulsion Motor.

Third: a single-phase motor having a wound rotor equipped with a commutator may be started as a repulsion motor, ¶ 372, and when normal speed is attained, a centrifugal device automatically short-circuits the commutator and at the same time lifts off the brushes, thus changing the machine to a single-phase induction motor.

372. Single-phase Commutator Motors. — Single-phase motors provided with commutators are of three general types, namely: plain repulsion, single-phase series, and repulsion-induction motor.

Repulsion Motor.— In the plain repulsion motor, a rotor exactly like a direct-current armature is placed in a magnetic field excited by an alternating current flowing through an ordinary single-phase stator winding. To secure the necessary torque the armature remains short-circuited in a line at a predetermined angle with the stator field flux, this being accomplished through brushes which rest on the commutator and are joined by a low-resistance connector. The pulsating flux produced by the alternating current flowing in the stator winding may be considered to have two components, one in the direction of the brush axis and the other perpendicular to this axis. The former component produces an electromotive force in the armature conductors and sets up a current in them, while the latter flux component reacts upon this armature current to develop torque. It is

necessary, therefore, that the brush axis be located on a line inclined at an angle to the axis of the field. Fig. 452 shows a simple diagram of the stator and rotor windings and the position of short-circuiting brushes for a two-pole repulsion motor. The operating characteristics of the plain repulsion motor have been improved by the use of a second set of brushes connected with a compensating field winding.

Single-phase Series Motor. — The series motor for operation on single-phase alternating-current circuits is about the simplest form of a single-phase commutator motor, and in general design is practically the same as a direct-current series motor except that all the iron used for the magnetic circuit must be laminated and a neutralizing or compensating field winding is very often used. Since the direction of rotation of a direct-current series motor remains unchanged if the current through it is reversed at its terminals, ¶ 281, it follows that any direct-current series motor will operate on alternating current. The armature of the series motor revolving in the alternating magnetic flux, will have several E. M. F.'s set up in its windings, as follows: first, an E. M. F. is induced in the armature by the periodic reversals of the flux from the field magnets; this is really a transformer action as this E. M. F. would be set up even if the armature was held stationary. Second, an E. M. F. is generated in the armature coils as they cut the flux when the armature rotates. Third, a reactive E. M. F. is set up in both the armature and field circuits due to their self-induction. The impressed E. M. F. must be high enough to overcome this reactive pressure and also the pressure generated by the rotating armature conductors in cutting the flux, this latter pressure being the same as the counter E. M. F. in a direct-current motor. Hence, the impressed alternating pressure must be greater than would be applied to a corresponding direct-current motor in order to overcome the above opposing pressures, and produce a current equal to that produced by the direct-current pressure. The inductive action of the armature and field windings causes the current to lag considerably behind the impressed E. M. F., thus resulting in a very low power factor. Further, an analysis of this motor shows that it has a starting torque but little greater than the torque at normal speed.

In order to improve the power factor and starting torque of the series motor some means must be taken to neutralize the armature reactive E. M. F., which is not essential to the operation of the motor. This neutralization is accomplished by the use of a compensating field winding, having such number of turns as to set up a magnetic field equal and opposite to that due to the current in the armature coils. The compensating winding may be energized by either one of two methods, the *conductive* or *forced compensation*, A, Fig. 453, in which the winding is connected in series with the main field winding and armature, or the *inductive compensation*, B, Fig. 453, in which is utilized the induced current obtained by short-circuiting the compensating winding upon itself. The latter method could of course only be used when the motor operates on alternating current, while the former method can be used with either alternating or direct current.

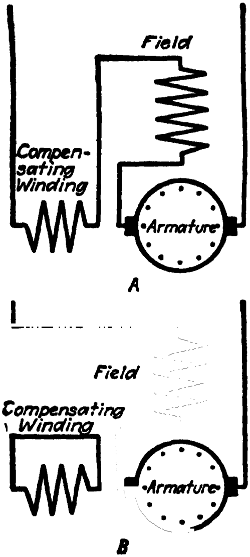


Fig. 453. — Connections of Compensated Single-phase Series Motor.

A — Conductive compensation.
B — Inductive compensation.

The objectionable sparking at the brushes of single-phase series motors is caused by the local currents produced by the E. M. F. induced in the armature coils which are short-circuited by the brushes, due to the periodic reversals of the field flux. The spark occurs as the short-circuit is opened when the commutator bars, to which the short-circuited coil is connected, leaves the brushes. This sparking is minimized by constructing the armature of many coils of but a few turns each, thus reducing the E. M. F. induced in each coil, and by the use of resistance leads between the armature conductors and the commutator segments.

Compensated series motors are well adapted for traction service for they exert a large torque at starting and less torque

at high speeds. They have come into quite considerable use for operating large locomotives and interurban cars; in several installations the motors are operated over some parts of the road with direct current.

An important commercial application of the principle of the series commutator motor is to be found in the construction of a small-size motor that will operate on either alternating or direct current, and for this reason termed a "universal" motor. This "universal" motor is widely used for operating vacuum cleaners, fans, electric drills and other small electrical appliances.



Fig. 454 — Single-phase Repulsion-induction Motor — General Electric Co., Type RI

Repulsion-Induction Motor. — The greatest application of the repulsion motor principle has been to improve the starting performance of the ordinary single-phase induction motor, and the compensating-winding feature of the repulsion motor is also often embodied in the single-phase repulsion-induction motor. A motor of this type, made by the General Electric Company, is shown in Fig. 454. The stator field consists of slotted laminations wound with two windings, a main winding and the compensating winding. The rotor is built of sheet steel laminations and its winding is the same as that on the armature of a direct-current series motor. The connections of the motor are shown in Fig. 455. These motors have four terminal leads brought out from the stator windings, permitting of the operation of the motor on either 110-volt or 220-volt circuits. By connecting adjacent pairs of these terminals in multiple, A to C and B to D, the motor can be operated on a 110-volt circuit, and by connecting terminals B and C together the two stator windings are connected in series and the motor can be operated on 220 volts. The compensating field winding, C, which is auxiliary to the main winding, is connected with a set of brushes termed the compensating brushes (5 and 7) and placed 90 electrical

degrees from the main short-circuiting brushes; the latter brushes are referred to as energy brushes (3 and 4) and have about the same angular relations to the stator field as have the brushes of a plain repulsion motor.

The compensating field which derives its current from the induced E. M. F. in the armature serves to correct the phase relation between the motor current and the voltage, thus producing high power factor at all loads. The compensating field

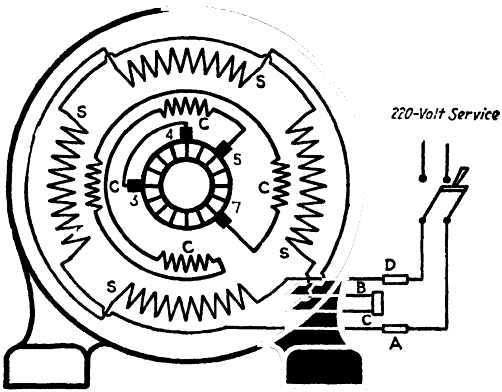


Fig. 455. — Connections of Type RI Four-pole General Electric Single-phase Motors.

also serves to restrict the maximum no-load speed and to lessen the variation of speed which usually accompanies changes of load. This type of compensated repulsion-induction motor possesses heavy starting torque at all loads, and after starting, operates practically as an induction motor. It may be wound for speeds above or below synchronous speed at standard frequencies. The speed of these motors may be made variable by inserting an adjustable resistance, in the form of a rheostat, in series with brushes 3 and 4, which are normally short-circuited.

Another type of compensated repulsion-induction motor, made by the Wagner Electric Manufacturing Company and known as type BK, has a rotor with two windings, a squirrel-cage wind-

ing consisting of copper bars placed in the bottom of the rotor slots, and above these bars, a regular direct-current armature winding connected with the commutator on which four brushes rest. The connections of the main and compensating stator windings with the brushes and line are shown in Fig. 156. The motor is provided with a centrifugal switch, S, which keeps the compensating winding open-circuited during the starting of the motor but places it in series with the main stator winding when the motor has acquired the proper speed. In operation, the squirrel-cage winding does practically all the work, very little of the load current being carried by the brushes and commutator. The amount of compensation can be varied by the lead L; when connected to point 7 maximum compensation is obtained, thus giving a leading current at light loads; with L connected to 8, normal compensation is secured, which gives nearly unity power factor at rated load. The particular advantages of this type of motor are: good power factor at all loads, practically constant speed at all loads, and a starting torque of approximately twice the full-load torque with the motor taking about three times full-load current.

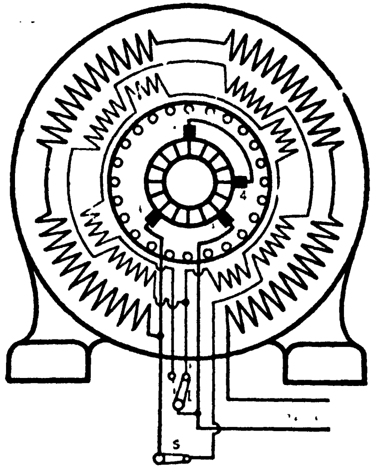


Fig. 156. — Connections of a Wagner Type BK Single-phase Motor.

A type of repulsion-induction motor without compensating winding, also made by the Wagner Electric Manufacturing Company, has a stator with a single winding and a rotor provided with form-wound coils the same as those of a direct-current motor armature. The carbon brushes, resting on the commutator during the starting of the motor, are all connected

electrically by a low-resistance conductor, thus short-circuiting the armature winding. The brushes are adjusted to such positions relative to the magnetic poles of the field, that a repulsive force is produced between these poles and the rotor poles, and the motor starts as a repulsion motor, the induced current in the rotor winding traveling the paths formed by the brushes. When the rotor has attained nearly normal speed, the brushes are no longer required and they are lifted from the commutator by a centrifugal device, while at the same time a ring of copper segments is forced into an annular opening in the commutator so as to short-circuit the entire rotor winding, thus transforming the rotor winding to the squirrel-cage form. The induced currents now traverse the individual coils of the rotor and the motor operates as a straight single-phase induction motor. It has practically constant speed, and will start under full load with a current about 1.5 times the full-load current.

373. Synchronous Motors. — Any single or polyphase alternator will run as a motor if it is connected to a source of alternating E. M. F. of the same frequency and pressure as it produces as a generator, provided it is first brought to its synchronous speed before the E. M. F. is applied. The term *synchronous* means in unison, or in step; so the rotor of a synchronous motor must revolve in unison, or in step, with the frequency of the alternating current supplied to it. For example, a synchronous motor having 24 poles and supplied with a 60-cycle current would run at a speed of 5 revolutions per second or 300 rev. per min., and when the motor has this speed it is said to be running in synchronism. This speed was obtained by dividing the frequency by the number of pairs of poles, Formula (146).

It has been stated that any alternator may be run as a synchronous motor; therefore such a motor is constructed in practically the same manner as the corresponding alternator in that it has a field excited from a separate source of direct current and an armature, either of which may revolve, requiring in addition, however, some means to bring the rotating member up to synchronous speed before the motor is connected to the alternating E. M. F.

The operation of the synchronous motor is due to the reaction

between a magnetic field of a fixed polarity produced by a direct current, and a field of constantly changing polarity set up by an alternating current, the revolving part running at a speed that will keep the magnetic poles of a fixed **N** and **S** polarity close to each changing pole of the proper opposite polarity that will produce a pull for rotation of the rotor always in one direction. If the simple form of alternator, shown in Fig. 308, has its armature coil connected to an alternating current that flows during one alternation in the direction from A to B, magnetic poles are produced in the armature loop that will be attracted by the oppositely-named poles of the field magnets; this attraction will tend to turn the armature in a direction opposite to that indicated by the arrow of rotation in Fig. 308. Before this magnetic attraction overcomes the inertia of the armature, the current through the loop will have been reversed and also its magnetic poles, thus tending to turn the armature in the opposite direction, that is, in the direction indicated by the arrow in Fig. 308. The alternations in the current occur with such frequency that the magnetic force in either direction does not persist long enough to produce rotation of the armature, with the result that it remains at rest, or it will simply vibrate. If, however, the motor armature is first brought to a speed corresponding with the frequency of the alternating current on which the motor is to be operated, then it will continue to revolve, because at synchronous speed the magnetic flux of field and armature are always in the same relative position.

The single-phase synchronous motor has no starting torque, whereas the polyphase type when operated without load is self-starting, as there is always some turning effort exerted on the rotor due to the fact that as the current in the stator coils of one phase reaches zero the current is increasing in the coils of the other phase or phases, resulting in a revolving field around the surface of the armature. With the field circuit open, this rotary flux sets up eddy-currents in the pole faces and reacts with them to develop torque. To aid the starting of polyphase synchronous motors, the polar faces of the rotating field have copper bars imbedded in parallel slots in the rotor core, the bars being connected to end rings forming an auxiliary cage

winding similar to the rotor winding of a squirrel-cage induction motor. A rotor constructed in this manner is shown in Fig. 457. With a rotor so constructed the motor will start, leaving the direct-current field circuit open, by applying the alternating pressure to the stator or armature windings.

Another advantage of the cage winding on the rotor is that it acts as a damper to prevent "hunting" of the motor. The

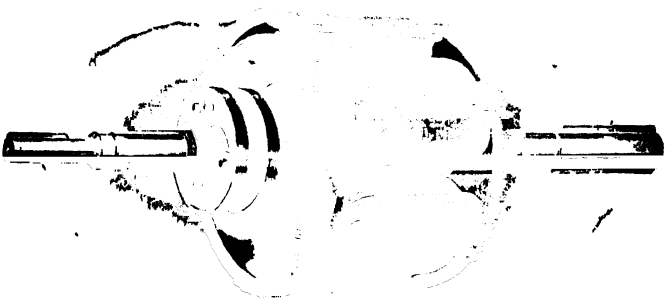


Fig. 457. — Rotor for Self-starting Synchronous Motor.

term "hunting" as applied to synchronous motors means the periodic fluctuations in rotor speed, or the periodic surging of current between the motor and the alternator supplying the current. If, due to a sudden increase in load, the rotor is slightly retarded, the armature will take more current from the line and will accelerate the rotor so as to shift the phase of its "counter" E. M. F. in respect to the impressed E. M. F. It will shift it too much, however, and the driving torque will be lessened until it is rendered insufficient for the motor load, whereupon the rotor will again lag, and so on. This oscillation of the rotor about its mean speed, that is hunting, is effectively reduced by the damping coils or cage of the rotor.

The use of synchronous motors is limited to large capacities where starting under load is not necessary, for the following reasons: the difficulty of starting, the small starting torque, and the fact that a direct current is required for the field excitation. Where it is possible to use induction motors, synchronous

motors are seldom used as they require more care than the induction type. The chief advantages of the synchronous motor are: its constant speed at all loads, and the power factor can at all times be controlled by varying the field strength. The current can be made to lead the impressed E. M. F. by this change of excitation, which fact is utilized in neutralizing the lagging current taken by induction motors that may be connected to the same circuit as the synchronous motor. Synchronous motors are frequently connected in transmission lines for the purpose of regulating their phase relations, the motor being run without load and the field excitation increased to suit the conditions. In such cases, where the synchronous motor operates only to correct power factor, it is termed a *synchronous condenser*, for the reason that its action on a circuit is the same as that of a condenser, ¶ 348.

374. Starting of Synchronous Motors. — Synchronous motors do not have sufficient starting torque to come up to speed under load, and therefore require an auxiliary source of power, such as an induction motor, to bring them up to synchronous speed. Thereafter, the electromotive force induced in its winding must have a phase difference of about 180° with the impressed voltage before the motor can be connected to the mains. A device, known as a *synchronizer*, is used to determine these two points. The simplest form of synchronizer consists of incandescent lamps connected across a switch inserted in the circuit of the motor to the supply circuit as shown in Fig. 458. The lamps will be brightest when the phase difference between the service and motor E. M. F.'s is zero, and will be dark when the phase difference is 180°, the lamps being alternately bright and dark as the motor comes up

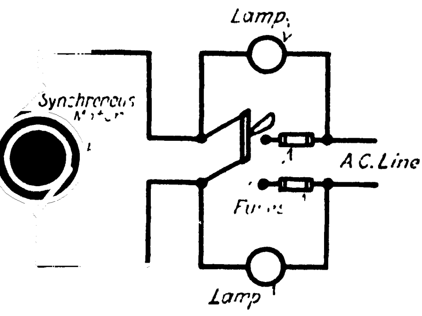


Fig. 458. — Synchronizing by Means of Lamps.

to synchronism. When synchronism is approached, the alterations in the brilliancy of the lamps become slower and finally become so slow as to permit closing of the main switch at an instant when the lamps are dark.

Instead of the lamps, an instrument known as a synchroscope, Fig. 459, is extensively used to determine when synchronism has been reached. The instrument is provided with a pointer which rotates at a speed proportional to the difference in frequency between the E. M. F. of the motor and that of the supply service to which the motor is being synchronized. When the machine is in synchronism and the pointer comes to rest at the top of the scale, the main switch may be closed, thus connecting the motor to the supply circuit.



Fig. 459. — Synchroscope.

Synchronous motors whose rotors are constructed with the self-starting auxiliary winding are started as induction motors with reduced pressure through the use of auto-starters similar to that shown in Fig. 449, the direct-current field circuit being open at starting. When the motor has reached nearly synchronous speed the full alternating pressure is applied to the stator winding and also the direct current to the revolving field windings. When starting in this manner precaution must be taken against the puncturing of the insulation of the field coils, due to the high voltage produced in them by the alternating flux. This is usually accomplished by placing a resistance, high or low depending upon the torque desired, across the entire field winding to take care of the induced voltage. A less practical method of opening the field circuit at several points with a multi-blade switch would require many slip rings.

375. Motor-Generator Sets. — The difference between a motor-generator set and a rotary converter is that the former consists of a motor mechanically coupled to one or more generators, with all machines usually mounted on the same bed plate; while the rotary converter is a single machine performing the functions of a motor and generator. In a motor-

generator set of two machines, both may be designed for direct current or both for alternating current, or again, one may be for direct and the other for alternating current. A motor-generator set of the first type converts from a direct current at one voltage to a direct current at another voltage, see ¶ 322. The second type is used chiefly for converting alternating current of one frequency to that of a different frequency, with or without a change in the number of phases, or in the voltage. This type, known as a *frequency changer*, is used to interlink power

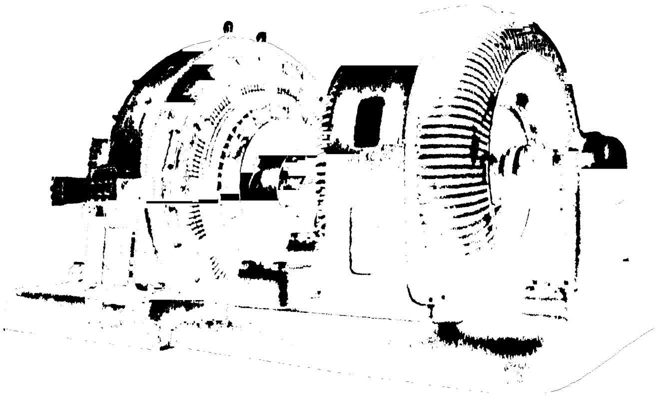


FIG. 460 — Motor-generator Set for Converting Alternating Current to Direct Current.

systems of different frequencies. The third and largest class is employed, like rotary converters, to convert alternating current to direct current.

The motor-generator sets of the third type are suitable for a large variety of uses, some of which are as follows: to obtain direct current for charging storage batteries, using the power furnished by alternating-current circuits, in connection with garages, railway signal systems, telephone circuits, etc.; to furnish direct-current for operating arc lights for stereopticon and motion picture outfits or similar work, where the flicker of alternating-current arcs is objectionable; and to furnish low-voltage direct currents for electrolytic work.

The general appearance of motor-generator sets is indicated in Fig. 460. This illustration shows a General Electric 155-kw. set composed of a 2300-volt revolving-field synchronous motor (*i.e.*, an alternator running as a motor) and a 250-volt direct-current compensated interpole generator.

QUESTIONS

1. Name four general types of alternating-current motors.
2. How can a rotating magnetic field be produced?
3. What are some of the advantages of the polyphase induction motor of the squirrel-cage type over a shunt-wound direct-current motor?
4. What is the function of an auto-starter such as is used with polyphase induction motors?
5. How does a single-phase induction motor differ in operation from a polyphase induction motor?
6. State three general methods used for the starting of single-phase induction motors.
7. Name three general types of single-phase commutator motors: state briefly how they operate.
8. What is a synchronous motor?
9. To what use are synchronous motors limited?
10. How are synchronous motors started and what means would you use to determine when the motor is running in synchronism?

LESSON XXXI

VACUUM TUBES

Electric Charges — Electrostatic Induction — The Electrostatic Generator — The Electron Theory — Low-Vacuum Tubes — X-Rays — The Fluoroscopic Screen — Corona — The Edison Effect — Three-Element Vacuum Tubes — Characteristics of Vacuum Tubes — Table XXII — The Piezo-Electric Effect — Questions.

376. Electric Charges. The purpose of a voltaic cell or an electric generator is to maintain a difference of potential between its terminals, so that when conductors are joined across these terminals electric currents will flow through them. Now suppose two bodies isolated in space to have a difference of potential between them, then likewise an electric current will flow in a wire which is connected between these bodies so long as this difference of potential continues. These bodies are said to be *charged*, and one of them is charged to a higher potential than the other. For convenience the body at the higher potential may be considered as *positively charged* and the other *negatively charged*. When a wire is connected between the bodies, electricity flows through it, that is, the electric charges are moved until there is no longer a difference of potential between them.

Charges of electricity can be established on a variety of substances by rubbing them with different materials. Hard-rubber, sealing-wax, rosin and sulphur when rubbed with a woolen cloth acquire a negative charge, while a glass rod rubbed with silk acquires a positive charge. Such charged bodies attract light objects, as small pieces of paper and pith, over short distances. While the forces exerted are small, their action can also be observed in larger bodies when supported so that they may move readily. It can be shown that *like charges repel* and *unlike charges attract* each other, exactly as with magnet poles, ¶ 3.

Experiment 111. — Place a hard-rubber rod, that has been charged by rubbing it with wool or fur, horizontally in a wire stirrup which is suspended by a thread. Hold near its ends another rubber rod similarly electrified and observe the repulsion between them. Repeat using a glass rod rubbed with silk; it will attract the suspended rubber rod.

The presence of an electric charge on a body can be readily *detected by means of a leaf electroscope, Fig. 461. It consists of two thin leaves of gold or aluminum foil* fastened to a rod, which is mounted by means of a good insulator in the top of a glass vessel, or a wooden box with two glass sides, so as to protect the leaves against drafts. If a body carrying a small charge is brought in contact momentarily with the electroscope, the rod and leaves will receive some of the charge and the leaves will repel each other, the amount of their divergence being a measure of the charge. To avoid giving the electroscope too large a charge, and thereby causing a violent separation and possible tearing of the leaves, it is better to use a proof plane (a small metal disk fastened to the end of a glass rod) for transferring a little of the charge from the charged body to the electroscope, rather than making direct contact. If a glass rod is the charged body, the electroscope will receive a positive charge. If thereafter the proof plane transfers some charge from an electrified hard-rubber rod the leaves will collapse, showing that positive and negative charges brought upon the same conductor tend to neutralize each other

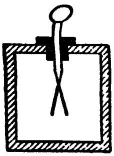


Fig. 461. — Gold-leaf Electroscope.

Experiment 112. — Make an electroscope, using a bottle and a metal rod for supporting the leaves Because of the difficulty of cutting and fastening gold leaves, it is better to use aluminum foil which can be cut readily with scissors when held between two sheets of paper. Upon completion, demonstrate that when a hard-rubber rod is rubbed with wool, the wool is electrified as well as the rod and that the charges are *unlike* Repeat for glass rubbed with silk.

This experiment and others performed with the greatest care show that the two kinds of electricity (positive and negative) are produced simultaneously and that their amounts are equal.

377. Electrostatic Induction. — Consider an electroscope in an uncharged or neutral condition, or what is the same thing, consider it to have equal charges of positive and negative electricity, Fig. 462(*a*). When an electrified rod is brought *near* it, the leaves of the electroscope will diverge showing that the neutral condition has been disturbed so that the two leaves have like charges, as shown in Fig. 462(*b*) for a negative *inducing charge*

on the rod A. The positive charge has been attracted by the inducing charge and the negative has been repelled. These charges on the electroscope are said to be produced by *electrostatic induction*. If the electrified rod A is removed the induced charges will neutralize each other and the electroscope will again be neutral as shown at (*a*).

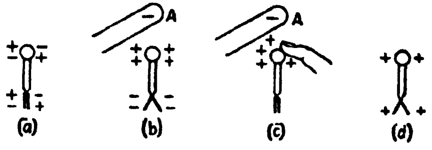


Fig 462. Charging by Induction.

If, while the inducing rod A is near the electroscope, the latter is grounded by touching it momentarily with a finger, the negative charge will escape to ground while the positive will be kept attracted by the inducing charge, Fig. 462 (*c*). Upon removing rod A, the positive charge will distribute itself over the electroscope system so that the leaves will again diverge as shown at (*d*). In this way a negative inducing charge places a positive charge on the electroscope.

The same process is utilized in the *electrophorus*, a device for establishing electric charges. It consists of a plate of hard rubber, rosin or sealing-wax, A in Fig. 463, which can be electrified by rubbing with wool or fur, and a metal disk B fastened to the insulating handle C. When the disk is placed upon the electrified plate, it actually touches the plate at but few points and only an inappreciable amount of its charge is removed by conduction. Virtually, then, the metal disk is brought very near rather than in contact with the plate, and therefore it is subject to electrostatic induction. A positive charge will appear on the lower surface of the disk and a negative charge on the upper surface. The latter is dissipated by touching the disk with a finger, and thereafter the disk may be removed by the handle C to enable the positive charge to distribute itself over the entire surface. This charge is often so great that sparks one-half inch long may be drawn from it.

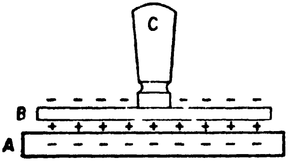


Fig 463. — The Electrophorus.

Since practically no charge is removed from the electrified plate, the process may be repeated many times before it is necessary to recharge the plate.

Electrostatic induction frequently causes disturbances in electric circuits. Fig. 464 represents an electric railway with overhead trolley supplied by a generator G located at the power station. Clouds, carrying electric charges, attract charges of opposite sign in the exposed trolley wire: the charges of the same polarity, being repelled, leak to ground slowly during the approach of the cloud.

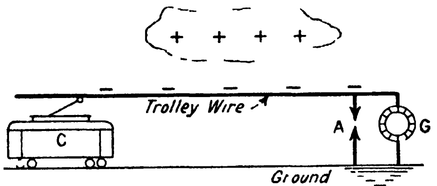


Fig. 464. - Electrostatic Induction in Exposed Circuits.

Likewise when the cloud passes by, the neutral state is again attained slowly and no harm is done. However, if the charge on the cloud while near the circuit is relieved suddenly, as by a lightning flash to another cloud or to ground, then the re-establishment of the neutral condition causes a surge at high potential through the circuit, causing damage to the generator G and the motor car equipment C. Protection is afforded against such surges by introducing lightning arresters at various places in the circuit, as at A in the figure. These arresters are short air gaps which break down when the surge reaches them and thereby produce temporary low-resistance paths to ground. As soon as the surge has passed, the high resistance of the gap must be restored automatically (usually by electromagnetic means), so that the generator will not remain short-circuited for more than an instant.

When telegraph and telephone circuits are located in parallel proximity to the lines of large alternating-current railway and power-transmission systems, the latter operating at voltages up to 150,000 volts, these circuits derive by electromagnetic and electrostatic induction sufficient voltages to interfere seriously with their proper transmission of signals. Fig. 465 shows the disturbing effect on a two-wire telephone line AB during the brief time that the alternating current in the disturbing wire

CD is growing from zero to its positive maximum value, the full and dotted arrows on the telephone line indicating respectively the currents produced electromagnetically (¶269) and electrostatically. The directions of these currents change repeatedly in unison with the current in the disturbing wire. An inspection of the figure will show that electromagnetic disturbances may be eliminated so far as the terminals are concerned by transposing

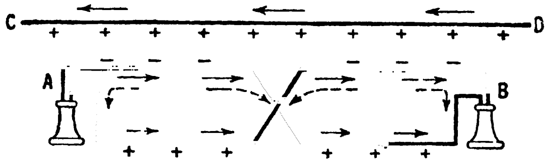


Fig. 465. — Induction on Communication Circuits.
Electromagnetic induction full arrows, electrostatic induction dotted arrows

the two wires of the telephone line at the center of exposure to the disturbing wire. However, electrostatic disturbances, while reduced, are not eliminated, but it is evident that such disturbances may be minimized by frequent transposition of the two line wires. When numerous aerial telephone lines are mounted on the same poles a careful consideration will yield a satisfactory arrangement of transpositions for the elimination of mutual disturbances as well as those occasioned by adjoining power circuits.

378. The Electrostatic Generator. The production of electric charges by induction can be carried out more conveniently by a rotating arrangement than by means of the electrophorus. A series of small disks is rotated near positive and negative electrified plates and the charges induced in the disks are collected to establish large potential differences. Such machines were devised by Toepler and improved by Holtz, and are called Toepler-Holtz machines and also *influence machines.* Fig. 466 shows a simple form of such a machine for demonstration purposes; it has one stationary plate for supporting a positive and a negative inducing body in the form of tin-foil sectors, and has one moving plate carrying six small disks of tin foil with metal contacting buttons.

The operation of the machine can be explained better with a

diagram in which the circular plates of the actual machine are replaced by concentric cylinders, Fig. 467. The outer cylinder is stationary and supports the plates having the inducing charges A and B, while the inner cylinder carrying the disks a to f is rotated clockwise. Stationary brushes are attached to collecting combs CC′, neutralizing rod N, and replenishers RR′, and make contact with the disks during their rotation.

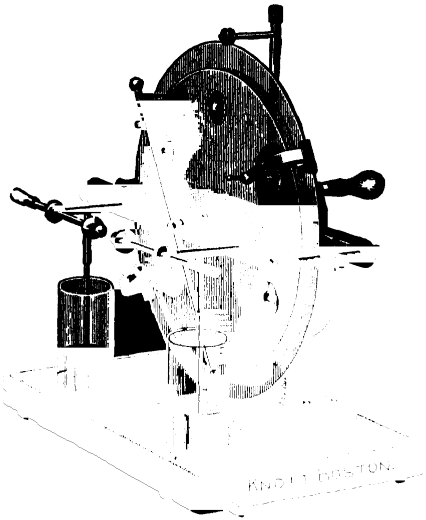


Fig. 466. — Toepler-Holtz Machine. Machine with 12-inch diameter revolving plate yields sparks 4 to 6 inches long

To trace the operation, consider a disk in position a, just after leaving the brush on collector C; there will be induced in it a negative charge on the outer and a positive charge on the inner surface. The latter will be removed by the brush on the neutralizing rod upon reaching position b, while the negative charge is carried to the brush on collector C′ at position d. Coincidently with this action, the diametrically opposite disk starting at position d loses its negative induced charge to the neutralizing rod at e and carries its positive charge to collector C at position a. Thus the purpose of the neutralizing rod, which makes simultaneous contact with two disks at positions b and e, is to transfer the positive induced charge in the upper disk to the lower one while transferring the negative charge of the lower disk to the upper one. The brushes at positions c and f remove slight amounts of the charges on the carriers to replenish the main inducing charges A and B. Continued motion of the carriers builds up + and − charges on collectors C and C′ respectively until a spark passes in air between their terminals TT′. The

machine is self-exciting, that is, the charges A and B are established by the machine itself, beginning with the minute potential differences due to contact of the brushes on the carriers.

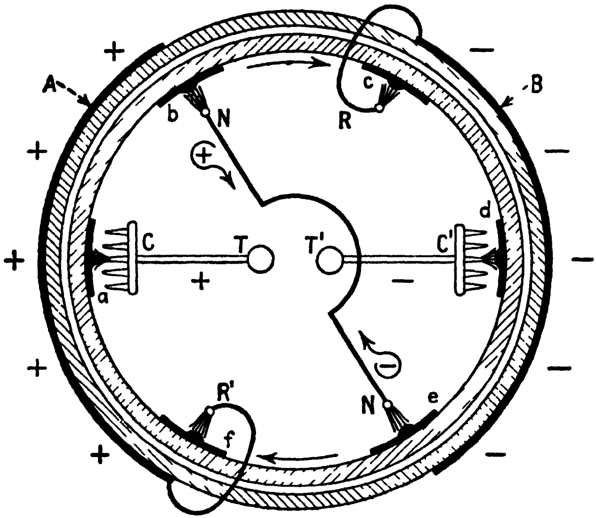


Fig. 467. — Diagram of Influence Machine.

379. The Electron Theory. — It is well known that all substances are built of molecules and that these in turn are built of atoms. Investigations show that there are about ninety kinds of atoms since that many exhibit chemical properties different from each other. A substance which has atoms of one kind only is called a chemical *element*, while a substance built of molecules with several kinds of atoms is termed a chemical compound.

It is now known to a high degree of probability that each atom is composed of a *nucleus* surrounded with *electrons*. The nucleus is always positively charged and the electrons always negatively charged. The latter are exceedingly small; an electron has a mass about 1/1800 of that of the lightest atom, namely the hydrogen atom. Some electrons can be detached from atoms, and this is apparently the result when two substances are electrified by rubbing them together. For example, when hard rubber is

stroked by wool, the former acquires a negative charge, implying that the wool has lost some electrons. This theory of electricity is termed the *electron theory;* it is extremely useful in explaining electrical phenomena.

Conduction of electricity in metals is explained by the electron theory on the basis that electrons may move freely between the atoms and molecules of such materials. When the electrons move they carry their negative charges with them, and moving charges are really electric currents. Since the positive charge resides on the nucleus of the atom, positive charges can move only when the atoms move; these cannot move freely in metals because of their relatively large mass. Consequently the flow of electricity through metals is due solely to electrons in motion, and obviously their direction of motion is from the negative terminal to the positive. In view of the fact that this direction is exactly opposite to the convention of *current flow* adopted many years ago and used throughout this book, the direction of movement of the electrons is termed the *electron flow* to avoid confusion.

In electrolytes both atoms and electrons move and carry their respective charges; this fact is demonstrated in electroplating where atoms of metals move through liquids and are plated on the electrodes. In such liquids conduction of electricity takes place by the movement of charged positive and negative units called *ions*, and the electrolyte is said to be *ionized.*

Air and other gases are very good insulators under ordinary conditions of pressure and temperature. In the arc light or in the mercury vapor lamp, for example, air or gas forms a part of an electric circuit and becomes a conductor. Such gaseous conductors are ionized and conduction takes place in a manner somewhat similar to that in electrolytes. Ionization of gases can be brought about by impact and by the action of certain kinds of rays.

Due perhaps to the presence of radioactive substances on the earth, positive and negative ions are found in the surrounding atmosphere. However, they are present in such limited quantities that their convection from place to place is inappreciable and, therefore, the electric conductivity of the atmosphere is very poor. When voltage is applied across two terminals located in air, the moving ions between them acquire more energy and collide with neutral atoms or molecules with enough speed

to knock off electrons. This process, called *ionization by collision*, results in separating a molecule into positive and negative ions when that molecule is hit with sufficient impact by a high-speed electron or atom. The greater the voltage the larger will be the number of ions formed and the greater will be their drift to the terminals. Consequently as the voltage is increased more and more, the number of ions will multiply with great rapidity and eventually the ionic drift (or current) will develop into a spark between the terminals.

The formation of ions can be increased very much by the action of X-rays, ultraviolet light, and the rays from radium and radioactive substances. For example, a charged electroscope will lose its charge quickly when an X-ray tube is operated in the same room, because the rays which it emits render the surrounding air electrically conducting.

380. Low-Vacuum Tubes. If the pressure on a gas is reduced the number of molecules per unit of volume naturally becomes less, and there is greater liklihood for an ion to go a long distance between collisions and acquire a speed sufficient for ionization; consequently there is greater conduction in gases at low pressures than at normal or high pressures under like voltages. This behavior can be observed when air is exhausted from a long glass tube while a high voltage (from an induction coil or electrostatic generator) is applied across two terminals sealed in the opposite ends of the tube. When the air pump is set in operation the spark discharge changes from a thin irregular line between the terminals to a broad band which, with a fair vacuum, fills the entire tube. The residual gas will be found to glow with a brilliant color and there will be luminous regions around the electrodes.

Tubes of different shapes containing gases at low pressure are available for showing the beautiful discharges with the use of small size induction coils. Such Geissler tubes, Fig. 468, are often made in sections of different kinds of glass and sometimes contain liquids and minerals. Upon connecting the terminals and starting the induction coil, the gases will glow and the

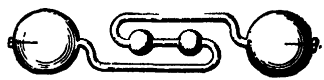


Fig. 468. — Geissler Tube.

liquids and minerals will fluoresce with brilliant colors due to the violent molecular bombardment.

381. X-Rays. — While experimenting with a Crookes vacuum tube (a tube having a higher vacuum than a Geissler tube) excited from an induction coil, Roentgen, in 1895, discovered that a sensitized photographic plate, concealed from daylight, but lying near the vacuum tube, indicated exposure to light when developed. Upon further investigation he found that a light was emitted from the vacuum tube, not perceptible to the human eye, but capable of penetrating many substances, as wood, thin metal and paper. He called this light *X-rays;* they are now also spoken of as *Roentgen rays*. When different substances are interposed between a protected sensitized plate and an excited vacuum tube capable of producing X-rays, the light penetrates them with different intensities, according to their density, so that the sensitized plate, upon development, shows the shadows of the objects interposed. A photographic print made from such a negative is termed a *radiograph.* When the human hand is placed between the protected plate and the tube the plate is scarcely affected directly underneath the bones, because they are nearly opaque. Considerable light penetrates the flesh and affects portions of the plate directly underneath it. A print made from such a negative gives shadows of the bones and a faint outline of the flesh. Radiographs of animal bodies can thus be made, and broken bones and foreign objects, such as bullets and needles, accurately located.

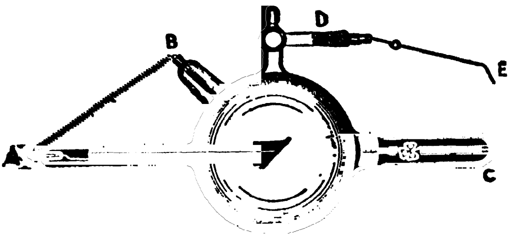


Fig. 469. — X-Ray Tube.

It has been determined by experiment that X-rays are produced upon the bombardment of metals by electrons going at high speeds (from one-tenth to one-half the speed of light, which is 186,000 miles per second). These negatively-charged par-

ticles are formed at the cathode when positive ions, attracted electrostatically by it, strike the cathode with sufficient impact to liberate electrons. Because of the great potential difference between the cathode and anode of the tube, these free electrons are violently repelled by the cathode and are projected as so-called *cathode rays* in straight lines upon the anode. This bombardment of the anode sets up waves analogous to, but much shorter than, the waves of light, and these waves of invisible light are X-rays. The action is somewhat akin to the emission of sound waves from a bell which is continually hit by shot for in this case also waves are produced by the impact of material particles.

Special forms of glass tubes are used for producing X-rays. One form in general use is shown in Fig. 469; it has three elec-

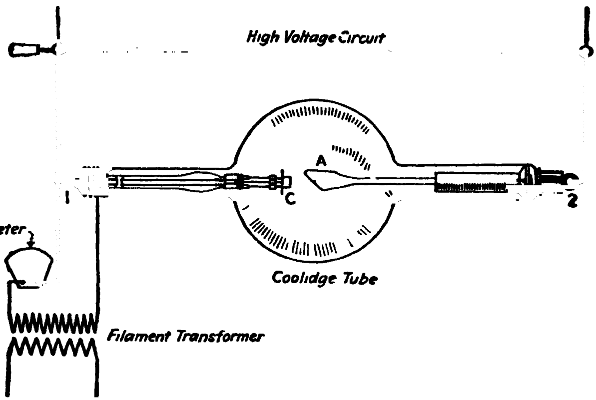


Fig. 470. — Connections of Coolidge X-Ray Tube.

trodes sealed in it, the anode A, the cathode C and the anti-cathode B. The cathode and anti-cathode are usually made of aluminum, while the anode has a platinum or tungsten target at the center of the tube and a long metal shield extending to the terminal. The electrodes are joined by platinum wires to the terminal clips in order to make the external connections, platinum wire being used through the glass because its expansion coefficient is the same as that of glass. The air is exhausted

from the tube so as to produce a high vacuum, the penetration of the X-rays emitted by the tube depending upon the degree of vacuum produced. The anode and anticathode are connected to the positive terminal of the source of supply and the cathode to the negative, the source of supply being a high-potential induction coil or transformer. A chemical preparation is placed in the *regulator tube* D which will emit a gas, and therefore slightly lower the vacuum of the tube, when a high-potential discharge takes place through it; this discharge is brought about by placing wire E near terminal C so that a spark will pass between these points when the tube is in operation.

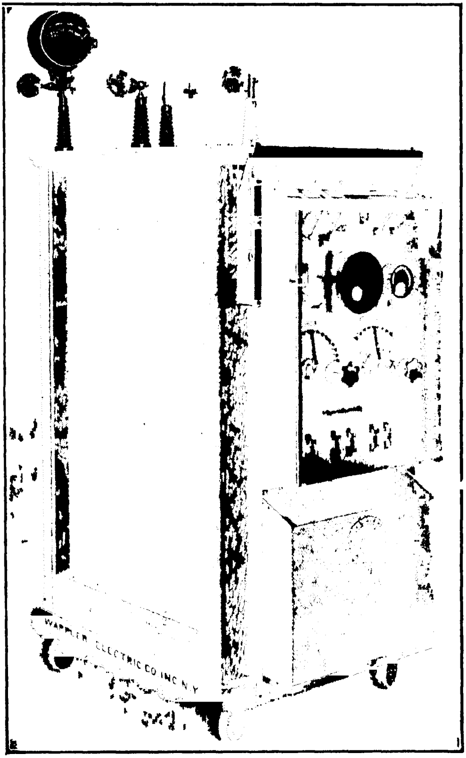


Fig 471. — Complete X-Ray Machine

The Coolidge X-ray tube (Fig. 470) consists of a glass tube of the shape illustrated exhausted until the proper vacuum is produced Supported in the tube is a cathode C, which is a filament of tungsten wire wound into a spiral, the filament terminals connecting to two brass pieces secured to the stem of the bulb, similar to an incandescent lamp base. The filament is heated electrically under a pressure of 10 to 12 volts, from a storage battery, or, when alter-

nating current is available, from the low-potential side of a transformer used to reduce the ordinary commercial voltages. A cylindrical tube of molybdenum with a flange, mounted concentric with the tungsten filament, and with its inner end projecting beyond the plane of the filament, acts to focus the cathode rays from the filament upon the target. This target or anode consists of a single piece of wrought tungsten, A, attached to a molybdenum rod, which is supported by a split iron sleeve carried out to the right-hand end of the tube.

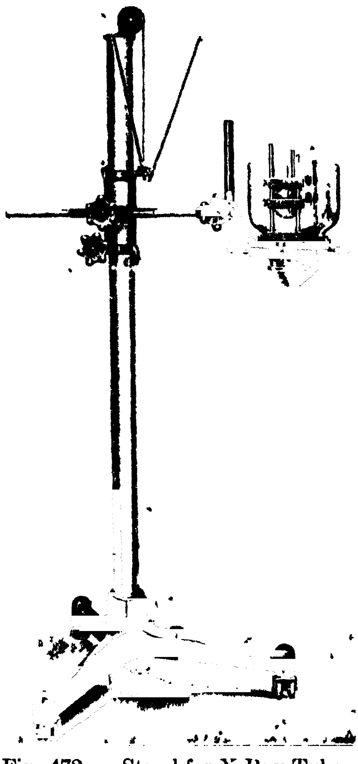


Fig. 472. — Stand for X-Ray Tube.

The Universal Coolidge tube is operated with a high voltage produced by an induction coil or a high-tension transformer. The filament must always be lighted before the high-tension current is applied to the tube. The high potential is applied to terminals 1 and 2 (Fig. 470), the positive being connected to terminal 2. If a high-potential transformer is used, some form of rectifier should be used in order that terminal 2 will be positive at all times. The tube should not be operated on voltages higher than that corresponding to a 10-inch needle-point spark gap in parallel with the tube.

Fig. 471 shows a complete X-ray machine made by the Wappler Electric Company for hospitals and medical roentgenologists. The machine is designed for 220-volt direct-current supply and is capable of producing a 12-inch spark in air

and an output of 150 milliamperes through an X-ray tube. The *current output can be varied by changing the number of primary turns and by a rheostat in the primary circuit.* Fig. 472 shows the tube stand which supports a lead-glass tube shield (in which the X-ray tube rests) with an aluminum lead-lined cone at its bottom for limiting the area of the rays.

382. The Fluoroscopic Screen. — In order that X-rays may be used to examine objects, such as the bones of the hand and foreign bodies in the system, use is made of a fluoroscopic screen. This screen consists of a piece of paper or cardboard coated with certain crystals, as platinobarium cyanide, or tungstate of calcium, which fluoresce under the action of X-rays. The light is of a pale greenish-yellow cast. If the hand be interposed between such a screen and the tube, the shadow of the bones can be plainly seen on the screen, the bones intercepting some of the X-rays, and thus causing the shadow. Wood readily allows the rays to pass through it, so that if a thick board be held between the hand and the screen, the shadow of the bones is still visible.

In the *fluoroscope* such a fluoroscopic screen forms the bottom of a box, the opaque sides of which slant inward toward the top, where an opening is left for observation. The daylight is thus excluded and the shadows of objects interposed between the fluoroscope and the tube are visible upon the enclosed screen.

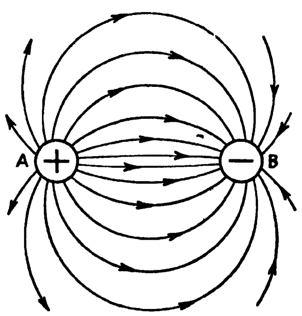


Fig. 473. — Electrostatic Field Between Two Unlike Charges.

383. Corona. — Since electric charges attract each other at a distance, just as do magnet poles, there must be present around such charges electric fields of force, called *electrostatic fields*, which are similar to magnetic fields, Lesson II. Such electrostatic fields can be represented by lines drawn between the charged bodies so that they indicate at each point the direction of force action experienced by a charged particle at that point. For example, Fig. 473 shows the electric field between two charged spherical

bodies A and B. The intensity of the field varies from place to place and depends on the force action upon a charged particle placed in the field. This force is naturally greater near the charged bodies A and B, and consequently the field intensity varies accordingly. The greater field intensity near the charged bodies is represented pictorially by the lines of force being closer together where they converge upon the charged bodies.

The strength of an electric field is measured in volts per inch. Because of ionization by collision, ¶ 379, air at ordinary pressure and temperature becomes convectively conducting and breaks down as an insulator when subjected to an electric field intensity of about 78,000 volts per inch. For alternating currents this value applies to the maximum value of the voltage wave, which means that the dielectric strength of air is 78,000 $\div \sqrt{2} = 55{,}000$ effective volts per inch. When the voltage between two charged bodies is raised, the field strength reaches the foregoing value first at the surface of the bodies, where the air will be ionized. This action will be accompanied by a luminous glow of red-violet color around the body, which glow is termed *corona*. Further raising of the voltage increases this brush discharge of electricity into the air until finally a spark is established between the bodies.

The phenomenon of corona is often visible on transmission lines which deliver power at high voltage. By considering A and B of Fig. 473 as the cross sections of two wires of a single-phase transmission line, this figure will represent correctly the electrostatic field around such a line. A transmission line is usually operated at a voltage less than the *critical voltage* at which corona appears in order to avoid the accompanying energy loss. The critical voltage depends upon the diameter, surface, and separation of the wires and is influenced by weather conditions.

384. The Edison Effect. — In the development days of the carbon incandescent lamp Edison experimented with a lamp which had a metal plate sealed inside the evacuated bulb and placed between but insulated from the two sides of the filament. He observed that when the terminal attached to this plate was connected with the positive terminal of the filament through a galvanometer, a current flowed through this instru-

ment, but when the connection was made to the negative terminal of the filament no current passed. This so-called Edison Effect could not be explained at the time, but it is now known that electrons are evaporated from hot bodies such as the incandescent filament and that, when the plate is positive with respect to the filament, these electrons are attracted to the plate and so set up an electric current. Further, when the plate is made negative (by connecting it with the negative end of the filament, it repels the electrons which are being evaporated from the filament, and since no electrons are emitted from the plate because it is relatively cool (that is, below a dull red heat), no current can flow.

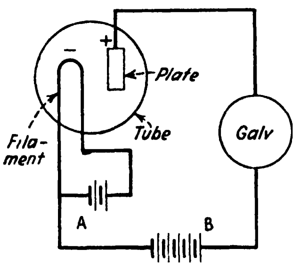


Fig. 474. — Flow of Electrons in Two-element Tube.

In Fig. 474 the potential of the plate is produced by a source of E. M. F. separate from that which heats the filament. The cold plate is rendered positive with respect to the filament by the B battery, and when the filament is heated to incandescence by the A battery electrons drift from it to the plate (electron flow), which means that the current flow (¶ 379) is directed from the plate to the filament. If the B battery were reversed no current would flow. This tube, containing the two elements *filament* and *plate*, therefore acts as a *rectifier*, permitting current to flow in one direction only. It is used in the *tungar rectifier*, ¶ 367, which is employed primarily in the charging of storage batteries from alternating-current mains, and in the *kenotron*, which is utilized to rectify high alternating voltages. The former contains argon or some other inert gas at low pressure and conduction occurs principally by the ionized gas; the latter tube is exhausted to a very high vacuum and conduction takes place by electrons only.

The vacuum tube may be made as large or small as practicable to suit the purpose at hand. For example, with a large tube, the galvanometer in the plate circuit of Fig. 474 might be replaced by the field coils of a direct-current motor, in which case the

tube would control the speed of the motor by making appropriate changes in the filament temperature. Such control or relay action is more conveniently accomplished by the use of the three-element tube, next to be explained.

385. Three-Element Vacuum Tubes. — The two-element tube described in the last section was used to some extent in place of a crystal detector in the early days of radio communication. It was termed a Fleming valve, after the investigator who showed its adaptation for rectifying the high-frequency alternating currents induced in a receiving aerial, so that their presence could be detected by telephone receivers relays or amplifiers. De Forest conceived the idea of using in the tube another element, made in the form of a mesh, for controlling the number of electrons going from filament to plate. The introduction of this mesh or *grid*, as it is called, into the vacuum tube has rendered it exceedingly useful as a sensitive detector of radio waves, as an amplifier of electrical signals and as a generator of high-frequency alternating currents.

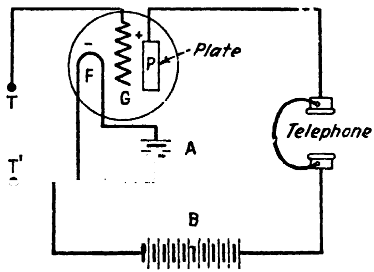


Fig. 475. — Three-element Vacuum Tube

Comprises a filament grid and plate within an evacuated glass bulb

The effect of the grid in the three-element tube, Fig. 475, is like that of a shutter which, opening and closing, controls the flow of electrons going through it from filament to plate. The action may be compared with that of a window shutter placed between a group of small boys armed with pebbles and, say, a tin plate at which the pebbles are hurled. When the shutter is opened, the pebbles go through and hit the tin plate, but when the shutter is closed no pebbles can go through it. The pebbles correspond to the electrons and the tin plate to the plate of the tube.

The opening and shutting effect of the grid is accomplished by alternately giving it positive and negative charges. When the grid is positively charged, it attracts electrons and increases their

flow from the filament to the plate. When the grid is negatively charged it repels the electrons so that they will not go to the plate. Consequently, when the grid is connected to a feeble source of alternating current (using terminals TT′ in Fig. 475), there will be alternately positive and negative charges on the grid, and the electron flow to the plate will be increased and decreased accordingly, thereby varying the direct current flowing through the telephone receivers. In this way the grid while taking practically no power can serve as a gate-valve in controlling relatively large currents flowing in the plate circuit.

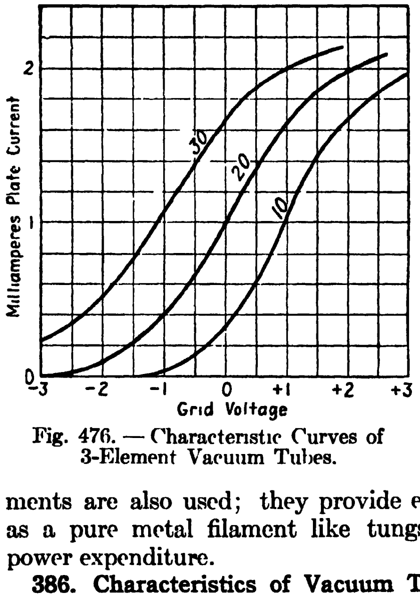


Fig. 476. — Characteristic Curves of 3-Element Vacuum Tubes.

In most vacuum tubes now available tungsten wire is used as the filament because it evaporates electrons at temperatures sufficiently low to give the filament a reasonably long life (about a thousand hours). Oxide-coated platinum filaments are also used; they provide electrons at the same rate as a pure metal filament like tungsten with about half the power expenditure.

386. Characteristics of Vacuum Tubes. — The behavior of vacuum tubes is best indicated by curves showing the plate current plotted against grid voltage. The curves of Fig. 476 show how the plate current of an ordinary radio detector or amplifier tube is increased by making the grid less negative and then increasingly positive. The curves apply to three different plate or B-battery voltages, 10, 20 and 30 volts, as marked on the chart. At zero grid potential, the plate currents are 0.32 milliamperes for 10 volts on the plate, 1 milliampere for 20 volts, and 1.64 milliamperes for 30 volts.

It will be found that with the grid held at constant potential

and the plate voltage varied, that the plate current will vary in a manner similar to the curves of Fig. 476. However the grid voltage is much more effective in controlling the plate current than is the plate voltage. Increasing the grid potential of the average tube used in radio receiving sets by one volt, will produce as much change in plate current as will result from increasing the plate voltage by from 5 to 8 volts. This figure is termed the *voltage amplification factor* of a tube.

The space between the incandescent filament and the plate of a tube is obviously occupied by a great many electrons, and therefore this space may be considered quite properly as having a *space charge*. Since this charge is all negative electricity, it will repel other electrons which are being evaporated from the filament and tend to force them back into it, thus limiting the plate current. Making the grid negative assists the space charge in limiting the electron flow, while making the grid positive neutralizes the effect of the space charge and allows more electrons to travel to the plate. Often a battery is used to give the grid a negative bias; a battery so used is called a C battery.

As already stated, increasing either the plate or grid voltage, or both, causes an increase in plate current, since more and more of the electrons evaporated from the filament are drawn to the plate. Naturally when all that are evaporated are drawn to the plate, there is no further use of increasing the plate or grid voltages. This limiting value of plate current is called the *saturation current*, and depends entirely upon the temperature of the filament. Thus it is clear that the filament temperature must always be high enough so that the normal plate and grid voltages can control the plate current, otherwise the tube would be useless. Tungsten filaments are operated at a white heat while oxide-coated filaments are heated to a dull red.

To comprehend the rectifying action of the three-element tube, assume the grid to be subjected to an alternating voltage varying between the maximum values of $+1$ and -1 volts, and that 10 volts are used on the plate, Fig. 476. When the alternating voltage passes through its zero value the plate current is 0.32 milliamperes, when at its negative maximum this current is 0.04 milliamperes, and when at its positive maximum the plate current is 1.02 milliamperes. Consequently the plate

current swings down 0.28, and up 0.70 milliamperes from its normal value for zero grid voltage; that is, the plate current is an alternating one having positive lobes $2\frac{1}{2}$ times as high as its negative lobes. If such a current passes through a suitable electrical device, the effect of the positive lobes will overbalance that of the negative lobes and the result will be similar to that produced by a direct current. This principle is made use of in detecting the high frequency oscillations set up in a radio antenna.

The following table gives the operating voltages and currents of some detector and amplifier tubes used in radio receiving sets:

Table XXII. Vacuum Tube Data

Radiotron	A Battery Volts	Filament Amperes	B Battery Volts: As detector	B Battery Volts: As amplifier	C Battery Volts	Normal Plate Milliamperes	Voltage Amplification Factor
UV-199	4.5	0.06	45	90	4.5	2.5	6.2
* UV-200	6	1.0	16 to 22.5	—	—	—	—
UV-201A	6	0.25	45	90 to 135	4.5 9.0	3 4	8
WD-12	1.5	0.25	22.5	90	4.5	2.8	5.6
UX-112	6	0.5	22.5 to 45	90 to 157.5	6 10.5	2.4 7.9	7.9

* Detector only

Experiment 113. — Connect a vacuum tube of the type used in radio receiving sets in the manner shown in Fig. 475, using a galvanometer in the plate circuit instead of the telephone receivers. Bring electrified substances such as hard rubber, glass and sealing wax, near the grid terminal and observe the deflection of the galvanometer. Verify the fact that positive and negative grid potentials respectively increase and decrease the plate current.

387. The Piezo-Electric Effect. — Certain crystals when subjected to pressure are found to be electrically charged at opposite ends or opposite faces, the charges being greater when plates are cut from the crystals along definite planes. This phenomenon, called the *piezo-electric effect*, results in producing an electric current when such a crystal is held between two in-

sulated metal plates and pressure is exerted upon them. Quartz, tourmaline and Rochelle salt are among the crystals which exhibit this property. The effect can be utilized, for example, to measure the great pressures produced by explosions, and by the converse effect, to set up mechanical vibrations when the metal coatings are connected to a source of alternating voltage of appropriate high frequency, ¶ 411.

QUESTIONS

1. What is a leaf electroscope and for what purpose is it used?
2. Explain how a body may be charged by induction.
3. How are inductive disturbances on electric circuits minimized?
4. Using a diagram of a Toepler-Holtz influence machine, describe in detail the operation of such machines in building up high potentials.
5. State briefly how the electron theory explains conduction of electricity in metals and gases.
6. Describe the Coolidge X-ray tube.
7. What is a fluorescent screen and how is it used in X-ray examinations?
8. Explain the Edison Effect.
9. What are the functions of the three vacuum-tube elements, namely: filament, plate and grid?
10. State the information which is given by the characteristic curves of a vacuum tube.

LESSON XXXII

TELEGRAPHY AND TELEPHONY

Single Morse Telegraph — Telegraph Repeaters — Duplex Signaling — Multiplex Telegraphs — Printing Systems — Telephone Instruments — Local-Battery Telephone — Common-Battery Systems — Automatic Telephones — Telephone Repeaters — Carrier-Current Transmission — Telephotography — Questions.

388. Single Morse Telegraph. — The transmission of telegraphic signals over wires is accomplished in a number of ways which give rise to the designations: single, duplex and quadruplex telegraphy, multiplex systems, automatic and printing telegraphs, etc.

The simplest method of signaling is that devised by Morse, called the *Single Morse telegraph,* which permits the transmission of one message at a time over an electric circuit. It consists of a line wire with a ground return and having one or more keys for opening and closing the circuit, and a number of sounders (¶ 180) for indicating audibly the presence of current in the circuit. Signals are transmitted by opening and closing the circuit for long and short intervals in accordance with a code, and are received by the clicks produced by the sounder armatures as they are attracted and released by the electromagnets.

On long telegraph lines the current received is small and consequently sensitive relays are used in the line circuits. A relay has a light armature and does not require as many ampere-turns as a sounder; further, the relay functions merely to open and close a local circuit which includes a sounder, rather than produce an audible response itself.

Fig. 477 shows the circuit of a single Morse telegraph between two stations using relays. When the line is idle, the circuit is kept closed by means of the circuit-closing switches s and s′ associated with the keys K and K′, causing current to flow continuously from ground G, switch s, battery B, relay R, line L, relay R′, battery B′, switch s′ to ground at G′. Assuming the operator at the left-hand station to send messages, he interrupts

the circuit by opening s (as shown in the figure) and then establishes current pulses by depressing his key for long and short intervals to produce the so-called dashes and dots of the telegraph code. These current pulses, flowing through the relay windings, cause the armatures A and A′ to be attracted and released, thereby closing and opening the local circuits which

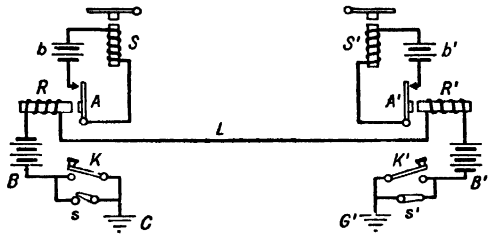


Fig. 477. — Single Morse Circuit with Two Relay Stations.

include the batteries b, b′ and the sounders S, S′. The sending operator thus hears his own signals and possible errors can be corrected promptly. When through sending, he again completes the circuit by means of the circuit-closer, thereby enabling the other operator to respond.

Assuming the telegraph line to be perfectly insulated from ground, the current which flows through the circuit can be calculated readily by Ohm's Law, ¶ 103. Let E be the total voltage impressed upon the line, R be the resistance of each of the n relays in the circuit, r be the resistance of the line wire per mile of length, and l be the length of the line in miles. Then the current flowing is

$$I = \frac{E}{nR + rl} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(153).}$$

If I be considered as the minimum operating current of the relays, then for a given line voltage, a given size of line wire, and a given resistance of relays, the maximum distance in miles over which signals may be sent is obtained from the foregoing equation by solving for l, namely

$$l = \frac{E - InR}{rI} \quad . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(154).}$$

Problem 154. — Over how long a line of No. 13 B. & S. copper wire could two 20-ohm sounders be operated on 120 volts, if the minimum current is 0.2 ampere?

From Table VI (page 67) the resistance of No. 13 wire is $5.28 \times 2.042 = 10.8$ ohms per mile. By Formula (154) the maximum distance for telegraphic transmission over this line is

$$l = \frac{120 - 0.2 \times 2 \times 20}{10.8 \times 0.2} = \frac{112}{2.16} = 52 \text{ miles.}$$

Problem 155. — If two 150-ohm relays requiring 0.04 ampere are used instead of the 20-ohm instruments in the preceding problem, what is the maximum distance over which telegraphic signaling is possible on that line?

By Formula (154)

$$l = \frac{120 - 0.04 \times 2 \times 150}{10.8 \times 0.04} = \frac{108}{0.432} = 250 \text{ miles.}$$

389. Telegraph Repeaters. — Overhead telegraph lines are supported by glass insulators mounted upon wooden, or sometimes concrete and steel, telegraph poles. These points of support offer leakage current paths to ground, and consequently not all of the current which starts out on the line reaches the receiving instrument. The insulation of the line in wet weather is much reduced and the received current is then very small. In order to assure sufficient current on long lines under all weather conditions, a *repeater* is introduced at intervals of from 300 to 600 miles to retransmit automatically over a section of the line the signal which it receives over the preceding section.

A repeater set for a single Morse telegraph consists of two relays and two transmitters which are electrically and mechanically arranged to allow signaling in either direction. Provision is made automatically to prevent a transmitter from breaking at the repeater station the line section which it controls when that circuit is repeating into the other. Fig. 478 shows the connections of the elements of one type of repeater which is used by the Western Union Telegraph Company.

The relays R, R′ are equipped with locking magnets L, L′, which are bridged respectively across the auxiliary contacts A, A′ of the transmitters T, T′. The armatures of the transmitters have flexible members insulated from the rigid portions so that when an armature is released the auxiliary contact A opens a little before the main contact M, and when the arma-

ture is attracted by its magnet it closes a trifle later than the main contact.

Normally, when no messages are being transmitted, the windings of the relays and transmitters carry current, but the locking magnets are short-circuited by the auxiliary contacts. Thus, the western line current flows through relay R, traverses contact M (which is closed) of the transmitter T, and passes through generator G to ground. Similarly, the eastern line current goes through relay R′, contact M′ and generator G′ to ground. Both relay armatures are held in their forward positions and as a result contacts x and x′ are closed. In conse-

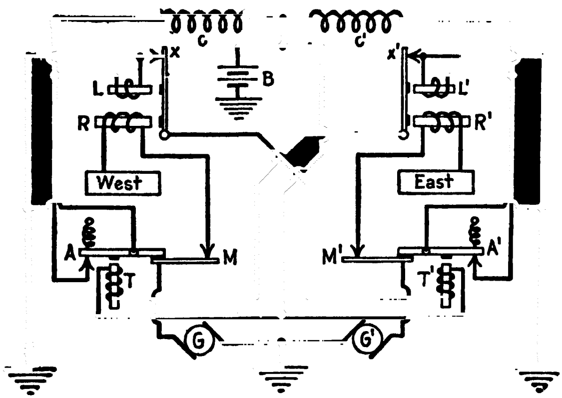


Fig. 478. — Connections of Shunt-locking Repeater.

quence, local battery (or generator) B energizes transmitter T through contact x′, and also energizes transmitter T′ through contact x.

When the western operator opens his key prior to signaling, relay R loses its magnetism and its armature falls back, thereby opening the magnet circuit of transmitter T′ at contact x. When the lever of this transmitter is released, contact A′ opens and then contact M′ opens. The former action removes the short-circuit around magnet L′ and current from battery B energizes it; the circuit includes inductance coil c′ which helps to speed up the action of the locking magnet. The armature of

the right-hand relay will therefore be kept attracted even if current flow through magnet R′ should cease, thereby keeping the magnet of transmitter T energized and preserving the continuity of the western circuit at contact M. The opening of contact M′ above referred to, causes the relay at the eastern station to release its armature, which action was desired by the western operator when opening his key. The result of closing the western key may be traced similarly.

390. Duplex Signaling. – In duplex telegraphy two messages are transmitted simultaneously in opposite directions over a single line circuit, without having the signals interfere with each other. Naturally four operators are required for such a circuit, one sending and one receiving operator at each station. As the message capacity of a duplexed line is twice that of the same line when operated as a single Morse circuit, considerable economy is effected in line equipment.

The receiving instrument at each terminal of a duplex line must be in circuit at all times ready to respond to signals sent from the opposite station. At the same time the relay must not respond to signals sent from its own station. This object is accomplished by using an *artificial line* at each terminal and connecting the relay so that currents sent from one station will divide between the actual line and the artificial line in such a way that the relay at the home station will not operate but the relay at the other station will. The artificial line is an assembly of resistances and condensers which together simulate the actual line.

The simplest type of duplex telegraph is illustrated in Fig. 479. The neutral relay R (and likewise R′) has two windings, identical as to number of turns and resistance, through which currents may flow in the same or in opposite directions around its iron core. The corresponding turns of the two windings are wound side by side so as to avoid the formation of consequent magnetic poles, ¶ 23, but for clearness the two windings are shown separated in the figure. Each artificial line A and A′ has a resistance equal to that of line L plus that of the terminal apparatus from the end-point of the line to ground. Coils H and H′ have resistances equal to the internal resistances of batteries B and B′ respectively; under this condition the resistance of the

circuit is unaltered whether the keys K and K′ are on the front or rear contacts.

The operation of this duplex telegraph circuit is simple. If neither key is depressed, no circuit containing an E. M. F. is closed and therefore no relay is actuated. The depression of one key, say K′, causes a current to enter relay R′ at the junction of the two windings and, because of the equality in resistance of the two paths to ground, the current will divide equally between the two coils; consequently their magnetomotive forces will neutralize and leave the core unmagnetized. The current which flows over the line to relay R at the left-hand station flows almost entirely through the first winding and through resistance H to ground; the remainder flows through the other winding

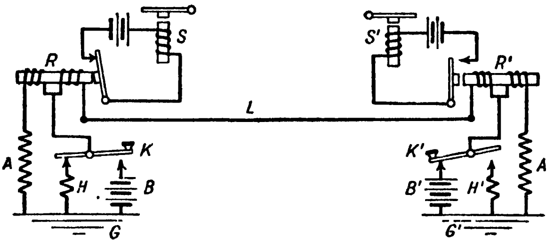


Fig. 479. — Differential Single-current Duplex Telegraph.

and artificial line A to ground. These two portions of the line current flow in the same direction through the coils of relay R and magnetize it. Consequently the depression of key K′ causes the actuation of relay R and sounder S, but not of R′ and S′.

The depression of both keys connects the two batteries in opposition and, since no current then flows in the line wire nor in the line coils of the relays, both instruments are actuated by the currents supplied by the home batteries through the artificial line coils. Thus, in this system, a relay at one station is energized whenever the key at the other station is depressed regardless of the position of the home key.

The resistances of the artificial lines are experimentally adjusted in practice so that the relays are not affected by movements of the home keys. Their resistance may, however, be

calculated on the assumption that the line is perfectly insulated from ground and devoid of capacitance with respect to ground; the result is expressed by

$$A = \frac{rl}{2} + \frac{1}{2}\sqrt{(rl + R)(rl + R + 4H)} \quad . \quad . \quad . \quad \textbf{(155)}.$$

where rl is the total resistance of the line wire, R is the total resistance of each relay, and H is the internal resistance of each battery.

Problem 156. Two 200-ohm relays are connected to the ends of a 1400-ohm duplex line. What should be the resistance of each artificial line if the internal battery resistance is 41 ohms? Neglect the effect of line leakage and capacitance.

By Formula (155)

$$A = \frac{1400}{2} + \frac{1}{2}\sqrt{1600 \times 1764} = 1540 \text{ ohms}.$$

The correctness of this solution may be checked by demonstrating that the total resistance from one line terminal to ground at that station is $100 + \frac{41(1540 + 100)}{41 + 1540 + 100} = 140$ ohms (¶ 108), and that the two paths to ground from the junction point of the relay windings each have $100 + 1400 + 140 = 1640$ ohms resistance.

Another system of duplex telegraphy utilizes polarized relays (¶ 181) and operates on *reversal of current direction* rather than by *change of current strength*. It is called a polar duplex (sometimes also a double-current duplex), and Fig. 480 depicts its

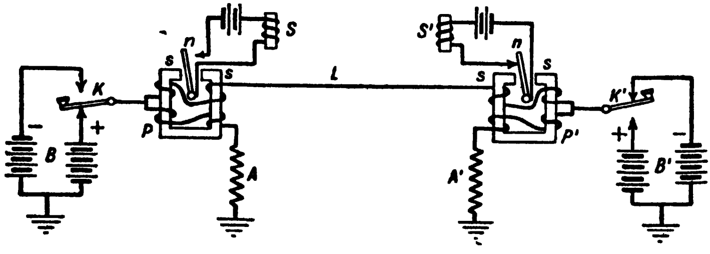


Fig. 480. — Polar Duplex Telegraph.

connections. The polarized relays P and P′ are differentially wound, as were the neutral relays in the preceding figure; the keys K and K′ control the polarity of the voltage applied by the

batteries B and B′ to the junctions of the relay windings. The letters n and s on the relay poles represent their magnetic polarity due to the permanent magnets alone.

When both keys are up, the negative terminals of batteries B and B′ are connected to the mid-points of the relay windings and therefore no current traverses the line nor the upper coils of the relays. Currents, however, flow in the lower coils, and their directions are such as to draw the relay armatures away from the sounder contacts, and consequently both sounders are idle.

If only key K is depressed, the positive pole of battery B is connected to the line and the conditions are exactly as represented in the figure. About twice as much current flows through the upper coils of the relays as through the lower coils, so that the operation of the relays depends upon the direction of current in the upper coils. The current in the upper coils of P strengthens the left-hand pole and weakens the right-hand pole, and consequently the armature stays away from its sounder contact. At the other station the current in the upper coils of P′ strengthens the left-hand pole and weakens the right-hand pole, and therefore the armature closes the local circuit and the sounder S′ responds. In like manner the depression of key K′ only will operate the sounder S.

When both keys are closed simultaneously, no current again flows over the line, because the positive poles of both batteries are in contact with the line. The currents in the lower coils are now in such a direction as to draw the armatures against the local-circuit contacts, causing both sounders to operate. Thus, the manipulation of one key controls the operation of the distant sounder, but does not control the home sounder.

By combining the two duplex systems herein described, Edison in 1874 devised the *quadruplex telegraph* for transmitting four messages simultaneously over a single wire without interference. The *neutral side* provides two channels of communication by means of changes in current intensity and the *polar side* provides two channels by means of current reversals.

391. Multiplex Telegraphs. — The term *multiplex telegraph* is applied to those systems, affording several channels of telegraphic communication over a single wire, which utilize the synchronous rotation of *contact distributors* at the two terminal

stations for assigning the line to corresponding transmitting and receiving devices.[1]

The method is illustrated in Fig. 481 for transmission in one direction only. Four keys are shown connected to contact segments at the transmitting distributor D, and four relays are shown joined to segments at the receiving distributor D′. When the moving arms of the two distributors are both on contacts 1, key K_1 will be in the circuit of relay R_1 and control its

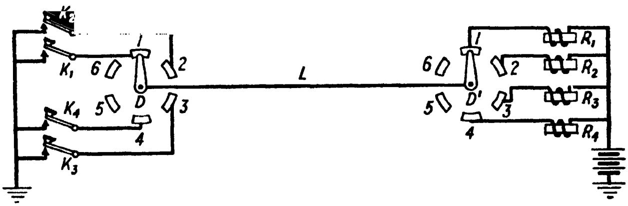


Fig. 481. — Scheme of Multiplex Telegraph Transmission.

operation; when the arms are both at contacts 2, key K_2 will control relay R_2, and so on. By having the arms at the two terminal stations always in step, each relay will receive signals only from the key marked with the same subscript, and there will be no confusion of signals. The speed of these synchronously-revolving arms is made sufficiently great so that they will be coupled with any one channel, say K_1R_1, one or more times during the short interval required to form a dot signal. By assigning the line in this way to the four sets of instruments, each set having exclusive use of the line for only a moment at a time, a number of channels of communication are possible over a single line.

Each telegraphic character is made up of short impulses rather widely separated as compared with their duration. The signals are rendered intelligible when transmitted by pole-changing keys and received by polarized relays. Two-way communication may be accomplished by introducing relays at the left-hand and keys at the right-hand stations in Fig. 481; each channel will then be the equivalent of a single Morse cir-

[1] Another method of multiplex telegraphy is described in ¶ 398.

cuit as in Fig. 477 Multiplex telegraphy, however, is usually carried out by polar duplex methods. Four polar duplex sets (Fig. 480), connected as in Fig. 481, would constitute a quadruple-duplex circuit and afford 4 telegraph channels in each direction over a single line.

It is absolutely essential that both contact arms occupy the same relative positions at all times. Such synchronous rotation is secured by the use of motors having tooth-wheel iron armatures and periodically excited field magnets, the contact arms being mounted directly on the motor shaft. Periodic field excitation is obtained by means of a reed which is kept vibrating

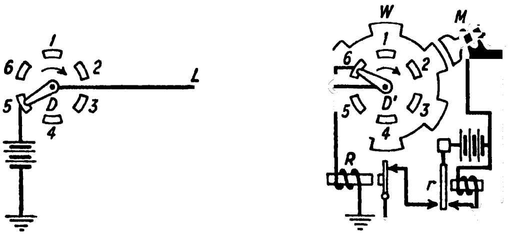


Fig. 482. — Method of Securing Synchronous Rotation of Distributors.

at its natural frequency. To maintain synchronism the distributor at one station sends to that at the other station one or more governing impulses during each revolution of the arm, which impulses control the speed of the distant motor.

One circuit arrangement for securing synchronous rotation is shown in Fig. 482; the vibrating reed and distributor motor being shown only at one station. The toothed wheel W of the distributor motor will advance one tooth every time the vibrating reed r makes one complete vibration, due to the impulsive currents reaching the magnet M every time the reed touches its front contact. The reed is kept in vibration electromagnetically in the usual manner, that at the right-hand station being adjusted one or two per cent faster than that at the left.

When the distributor arm D′ reaches contact 6 while the other arm D is still on contact 5 (as shown in the figure), a current pulse will flow over the line L and through relay R, and cause its

armature to be attracted. This action opens the vibrator circuit for an instant, thereby retarding slightly the vibration of the reed and the rotation of distributor arm D′. When both arms are in step in passing over contacts 5 or over contacts 6, no governing impulse is transmitted to the relay.

392. Printing Systems. — In recent years hand transmission of telegraph signals at speeds of approximately 30 five-letter words per minute has been largely superceded by automatic methods at much higher speeds. Such methods involve the preparation of the messages on tapes by means of keyboard perforators, and the feeding of these tapes to a pole-changing

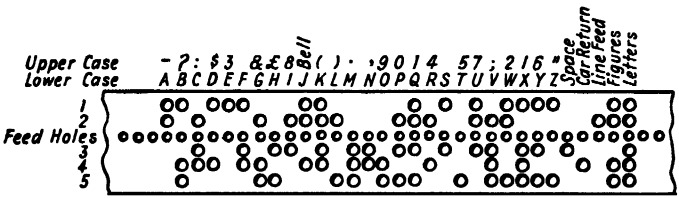


Fig. 483. — Printing Telegraph Code.
The large holes in one vertical line constitute the perforations for the character marked above them.

transmitter. The current pulses are received at the other line terminal by a group of polarized relays, which selects the letters of the messages and cause these letters to be printed automatically on a page or tape.

The code selected for most printing systems has the same number of impulses for each letter, namely five. Such a five-unit code provides 32 combinations of positive and negative impulses for the operation of one or more of five selecting relays. These select any one of the 26 letters of the alphabet or any of the functions such as: space, line feed, carriage return or shift. The code is given in Fig. 483, which represents the tape with the characters perforated in five lines, two above and three below the feed holes used for advancing the tape through the transmitter. A perforation in the tape means that the transmitter plunger passing through it will cause the negative terminal of the battery (or generator) to be presented to the line; thus, for the letter S, the polarities presented are successively −, +, −, +, +.

The principle of the printing telegraph is illustrated in Fig. 484. Motor-driven distributor arms D and D′ at the two stations are maintained in synchronism, as explained in the previous section. Five pole-changers are shown at the transmitting station connected to 5 segments in one quadrant of the distributor, and five polarized relays are similarly connected at the receiving station. When transmitting the letter S, for example, pole-changers 1 and 3 will be depressed so as to present

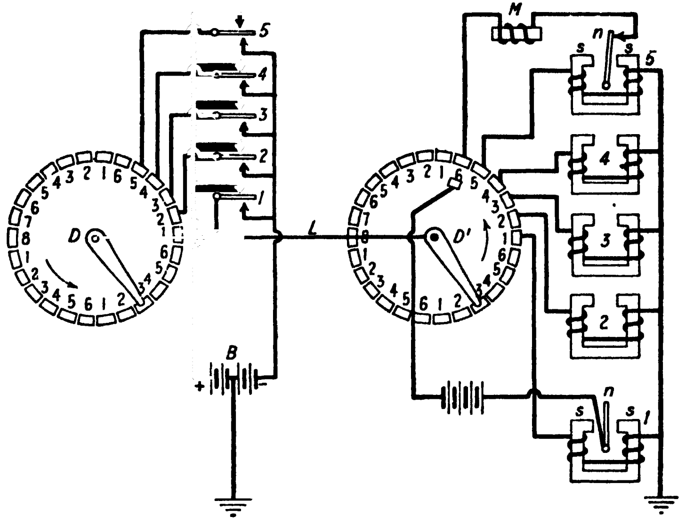


Fig. 484. — Actuation of the Selecting Relays in a Printing Telegraph.
Contacts 7 and 8 are used for synchronizing as in Fig. 482.

the negative terminal of battery B to the line L, and pole-changers 2, 4, and 5 will present the positive terminal. At the receiving station the directions of the current pulses through the polarized relays are such as to move the armatures of only relays 1 and 3 to the " marking contacts " at the right.

Selection of the printer magnets by the five polarized relays is illustrated in Fig. 485. Relay 1 is equipped with two contacts, relay 2 with four contacts, relay 3 with eight contacts, etc. The figure indicates the selection of the magnet for letter S. The

printing of the character so selected is accomplished when the distributor D′ bridges contacts 6 (also in Fig. 484), thereby energizing the magnet M which brings the type and paper into contact.

By using differentially-wound polarized relays and artificial lines, the arrangement just described may be adapted to duplex

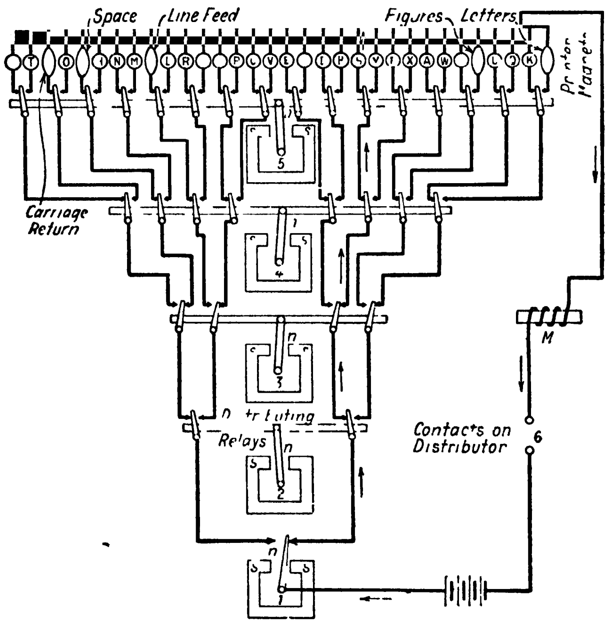


Fig. 485. — Selections of Printer Magnets.

Relay armatures 1 and 3 are shown on their right-hand contacts and armatures 2, 4 and 5 are on the left, this combination sets up letter S

transmission, the messages being received in printed form at both ends. Further, by utilizing the other three quadrants of the distributor for three similar sets of duplex terminal apparatus, multiplex transmission is obtained which affords eight channels of communication over a single wire. If the distributors revolve at 180 rev. per min., each transmitter will send 36

five-letter words per minute; this means a total carrying capacity for the eight channels of 36 × 8 = 288 words per minute.

393. Telephone Instruments. — In the transmission of speech by telephone, the transmitting instrument produces a variable current having the same characteristics as the sound waves incident upon it, and the receiving instrument converts this variable current into sound waves, thereby reproducing the original sounds. The essential parts of the telephone set are, the *transmitter*, which contains a resistance to be varied by the sound waves impinging upon its diaphragm; the *receiver*, which reproduces the sound waves by means of a diaphragm that is attracted by an electromagnet energized by the variable current; an *induction coil* for localizing the transmitter circuit and thereby rendering it more effective; a *hook switch* for completing the circuit of the "voice currents"; and a *ringer* for securing the attention of the party desired. In the telephone set of the so-called magneto system, there are required in addition a source of alternating and one of direct current; these are respectively a magneto (¶ 279) and a dry battery.

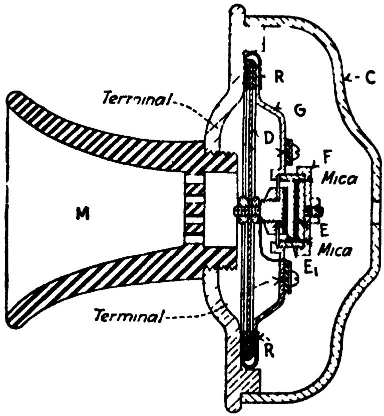


Fig. 486. — Telephone Transmitter.

Transmitter. — A cross section of a telephone transmitter is shown in Fig. 486. The diaphragm, D, of thin iron or aluminum is placed opposite a hard-rubber mouthpiece, M, and behind the diaphragm is mounted a brass chamber containing the transmitter electrodes, which are polished carbon disks. The larger of these disks, E, is fastened within the brass chamber F, which is screwed to the metal cup, G; the front carbon, E_1, is fastened to the center of the diaphragm and carries a mica washer, the outer edge of the washer being clamped to the cup G by the chamber F. The space between the carbon electrodes

is thus completely closed and is filled with coarse granules of carbon. The sound waves from the person speaking into the mouthpiece cause a vibration of the diaphragm and also of the electrode E_1 fastened to it; this produces a variable pressure upon the granular carbon, thus altering its resistance and causing a variation in the current flowing through the transmitter. The transmitter parts are mounted in a metal case C, which is supported by an adjustable clamp hinge. The two electrodes are insulated from this case by the insulating ring R.

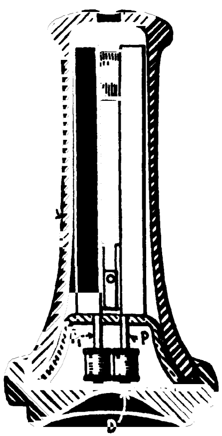


Fig. 487. — Bipolar Telephone Receiver.

Receiver. — The bipolar receiver, shown in Fig. 487, consists of a horseshoe permanent magnet with soft iron pole pieces P and P_1. Each pole piece is surrounded by a coil of very fine copper wire. Directly in front of the poles is placed a thin sheet-iron diaphragm, D, which must not touch the pole pieces at any time. One of the pole pieces attached to the permanent magnet is of north polarity and the other south polarity, and the diaphragm, which forms a part of the magnetic circuit, has a S-pole induced in it where the magnetic lines enter it and a **N**-pole where the lines leave the diaphragm. The diaphragm is constantly bent toward the pole pieces, due to their attraction for it. The coils on the pole pieces are so connected that the current when flowing in one direction will set up a magnetic force tending to strengthen the field of the permanent magnet and when flowing in the opposite direction will tend to weaken the field of the permanent magnet. The diaphragm will be drawn nearer to the pole pieces when the direction of current in the coils is such as to increase the field of the magnet, and when this current ceases, the diaphragm will spring back to its normal position; when the current in the coils causes the magnet's field to be weakened the diaphragm will recede from the pole pieces, and will be then drawn back toward them as this current stops. With an alternating current flowing in the receiver coils, the diaphragm will oscillate to and fro in accord-

ance with the current reversals. When used with a telephone transmitter, the receiver diaphragm will vibrate in the same manner as that of the transmitter, thus reproducing speech.

Induction Coil. — The induction coil localizes the transmitter circuit so that the variation in resistance produced by the transmitter will be a large proportion of the total resistance of its circuit. For example, if the transmitter changes its resistance under a given pressure by 25 ohms, then it will produce a resistance change of only 5 per cent in a line circuit of 500 ohms, whereas it will produce a change of 50 per cent in a local circuit of 50 ohms. It may also be used to raise the voltage of the line current in order to overcome the line resistance. Another function of the induction coil is to change the pulsating direct current coming from the battery and transmitter into an alternating current. The construction of a telephone induction coil is practically the same as described in ¶ 270; that is, it consists of an iron core, a primary and a secondary winding, but has no vibrator. The magnetic flux in the iron core increases and decreases according to the fluctuations in the current flowing through the primary winding, and this varying flux cuts the secondary winding and sets up an induced voltage that reverses in direction as the magnetic field is increased and decreased, thus producing an alternating current.

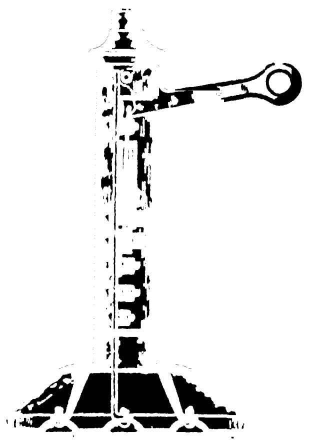


Fig. 488. — Cross-section of Desk Stand Showing Hook Switch.

Hook Switch. — The hook switch, shown in Fig. 488, is used for connecting and disconnecting the circuits of the transmitter and receiver. The switch is actuated by the weight of the receiver; with the receiver on the hook, the lever is held down against the action of the hook spring and causes two contacts to be held open; with the receiver off the hook, the lever allows the switch springs to close the talking and listening circuits.

Ringer and Magneto. — The ringer used in telephone signaling consists of the polarized bell described in ¶ 181. The generator used for producing the current for operating the ringer is a magneto which generates an alternating current according to the principles explained in Lesson XXIII; its construction is described in ¶ 279.

394. Local-Battery Telephone. – The telephone instruments just described may be connected as shown in Fig. 489 to form what is called the *bridging telephone set.* Two or more of such sets may be connected across the two line wires and communication established between any two sets. In somewhat larger telephone systems the subscribers' sets are connected to a central office where provision is made to interconnect these sets for conversation. Since each subscriber's set has a battery for the actuation of its transmitter circuit, the system is called a *local-battery* telephone system.

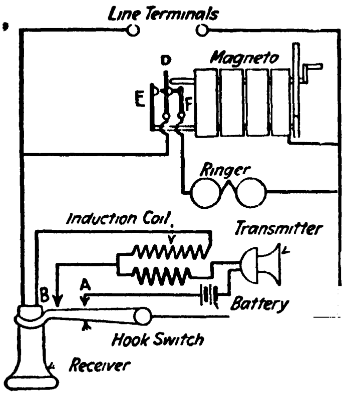


Fig. 489. — Connections of a Bridging Telephone

In the bridging set, Fig. 489, the generator is equipped with an automatic switch that opens the generator circuit when it is not in use, so that the low-resistance armature will not shunt the "talking apparatus." The armature coil is connected with the frame of the generator and with spring E. When the generator is turned by hand, its shaft moves a little to the left and causes springs D and E to touch, thereby introducing the armature into the line circuit, and also opening the ringer circuit at F. When not in use, the generator will be open circuited and the ringer will be connected across the line terminals.

The manually-operated telephone switchboard used with local-battery subscribers' sets comprises means for signaling and conversing with the switchboard operator, for calling subscribers, and for connecting and disconnecting the lines of any

two subscribers. The lines are brought into the central office through protectors and lightning arresters, and terminate in signals and in switch *jacks*. The switchboard is provided with flexible conductors having plug terminals that fit properly with the contacts of the jacks. Two of these conductors coupled together with control apparatus constitute a *cord circuit*. Such a circuit includes two switching keys: a *listening key* for connecting the operator's set to the circuit, and a *ringing key* for applying alternating current to the line in order to call the desired subscriber.

Fig. 490 illustrates how two subscribers' sets are connected through a central office. The cycle of operations follows: when

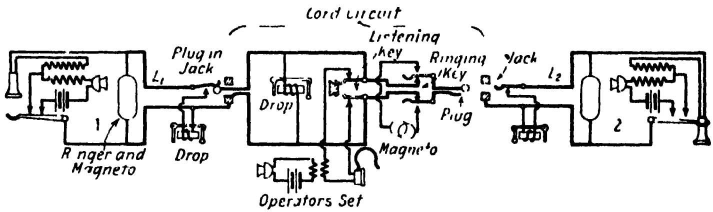


Fig 490. — Two Bridging Telephone Sets Connected through a Central Office Switchboard.

subscriber 1 turns his magneto, a current will flow through line L_1 to the central office and energize the annunciator drop associated with that line. This secures the attention of the operator, who inserts the *answering plug* of a cord circuit into the jack. The operator then depresses her listening key, thereby connecting her telephone set to the line (as shown), and requests the called subscriber's number. She then inserts the *calling plug* of the cord circuit into the jack of the called subscriber's line, and depresses the ringing key to send alternating current over line L_2 in order to call that subscriber. When he answers, the operator releases the keys and the connection is complete. To secure disconnection, either subscriber turns his magneto; a current will then flow through the *supervisory drop* bridged across the cord circuit, and its actuation is a signal to the operator to pull down the connection.

The central offices of a telephone system are connected to-

gether by *trunk lines* and *toll lines*, so that a subscriber desiring communication with another located in a different district or city may be connected with him through the switchboards located in their respective offices.

395. Common-Battery Systems. — In large communities where more rapid telephone service is demanded, the so-called *common-battery system* is used. In this system current for the talking and signaling circuits is supplied from a central or common source instead of from batteries and magnetos located at each subscriber's telephone set. The common source of supply for the talking circuit is generally a storage battery located at the central office. In a common-battery system the subscriber's telephone equipment is somewhat different from that of a local-battery system; for example, the transmitter is of higher resistance, due largely to the fact that the voltage in a common-battery system is higher than in the other system.

Fig. 491 shows the connections of a common-battery telephone set which is widely used in this country. The equipment consists of transmitter, receiver, ringer, induction coil, hook switch and condenser. The function of the condenser is twofold: it prevents the direct current from flowing through the ringer, and it improves the action of the induction coil, thus increasing the sensitiveness of the set. In the different telephone connections used in practice, the points of connection for the condenser will differ, the condenser performing either or both of the above mentioned functions according to the system of connections used.

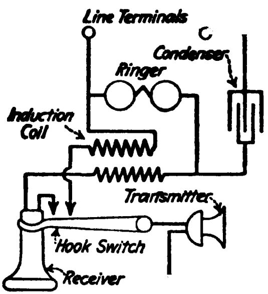


Fig. 491. — Connections of Telephone Set in a Common Battery System.

From the diagram of connections (Fig. 491) it can be seen that with the receiver on the hook no direct current can flow, but an alternating current may flow over the line to operate the ringer, since that circuit is completed through the condenser. With the receiver off the hook, the receiver is connected in series with the condenser and both windings of the induction coil across the line terminals, and will

respond to the pulsating currents set up by the distant transmitter. The direct current from the line flows through the primary of the induction coil and the transmitter, and the line current while speaking will fluctuate according to the vibrations of the transmitter diaphragm.

In the common-battery switchboard used by the Bell System and shown in Fig. 492, the common battery B is connected

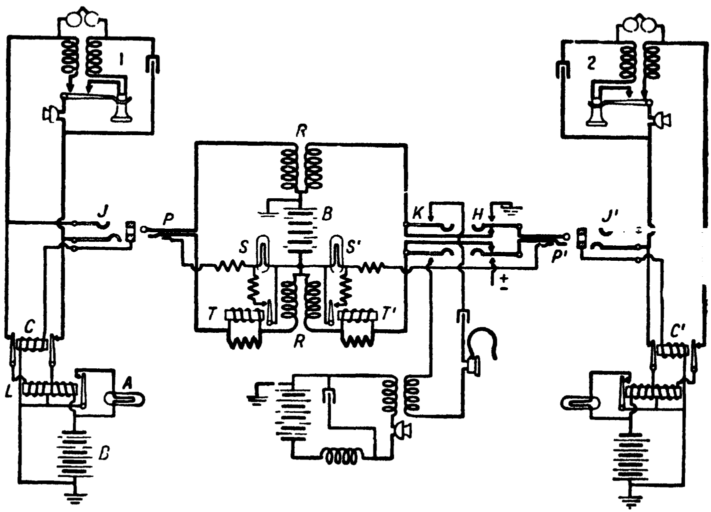


Fig. 492. — Circuit of a Common-battery Central-office Switchboard.

across the cord circuit through the four windings of a *repeating coil* R; all other cord circuits of the switchboard being similarly connected to the same battery. The other three batteries represented in the figure are in reality the same as battery B, but are shown separated for the sake of clearness.

The establishment of a connection between the two subscribers proceeds as follows: When subscriber 1 lifts the receiver from the hook, current from battery B_1 flows through both windings of the line relay L to the subscriber's set; this current energizes the relay and lamp A lights. The operator, observing this signal, inserts the plug P of a cord circuit into the jack J.

Current now flows from battery B to ground, through cut-off relay C', through the sleeve strands of jack and plug, and through the supervisory lamp S back to the battery. This current causes the armatures of the cut-off relay to be attracted and remove the signaling apparatus from the calling subscriber's line. Current will continue to flow to the subscriber's set, now however from battery B through the repeating coil R and the supervisory relay T. Signal lamp S thus receives current enough to illuminate it, but it is shunted by the actuation of relay T; as a result the lamp merely flashes and goes out.

The operator next depresses the listening key K and ascertains the number of the desired subscriber. Thereupon she inserts the answering plug P' into the jack J' of his line, and depresses the ringing key H. The insertion of the plug permits a current to flow from battery B, through cut-off relay C' and

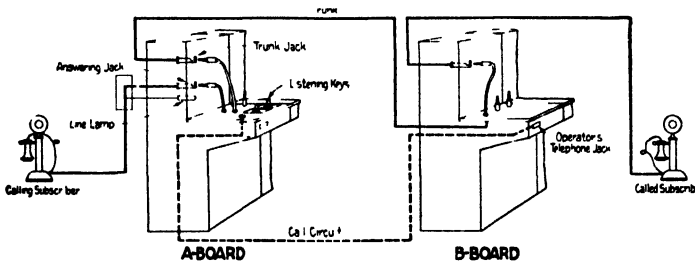


Fig. 493. — Interoffice Telephone Connection.

supervisory lamp S', lighting that lamp. This lamp will be extinguished when the called subscriber raises his receiver from the hook, for then direct current will flow from battery B to his set through supervisory relay T', which current operates the relay to shunt the lamp. After the conversation, the replacement of the receivers upon the hooks will prevent direct current from flowing to the subscribers' stations, relays T and T' will be released, and supervisory lamps S and S' will light. Upon receiving this signal, the operator takes down the connection.

Communication between subscribers connected to different central offices is established through two cord circuits, one located at the switchboard of each office. The call is handled at

the originating office by the *A-operator*, and she tells the *B-operator* at the terminating office over a *call circuit* to establish connection between the interoffice trunk and called subscriber's lines. Fig. 493 shows the scheme of connection. On the keyshelf before each A-operator there is a call-circuit button for each office to which she may be required to make a connection; the depression of one of these buttons connects her headset with that of a B-operator in the corresponding office.

396. Automatic Telephones. In an automatic or machine-switching telephone system the connections are completed by devices set into action directly by the subscribers. The subscriber's telephone set is of the usual form, but contains in addition a calling switch known as a *dial*. This dial has ten finger holes marked with letters and figures. A letter or figure is dialed by inserting the finger tip in the corresponding hole and turning the dial until the finger strikes a stop; upon releasing the finger the dial returns at a definite rate and sends an appropriate number of impulses to the central office. In a large community the numbers assigned to telephone subscribers involve seven digits, the first three are the first three letters of the central office name, and the rest are numbers.

Each subscriber's line terminates at the machine-switching office in a pair of terminals appearing before a group of switching selectors; these are called *line finders* because their function is to find calling lines. When a subscriber lifts his receiver from the hook prior to dialing, the line circuit is closed and a relay is operated. This relay causes an idle line finder to trip the proper brush and then move to the subscriber's line terminals. At the same time a *sender-selector* attached to that line finder chooses an idle *sender*. These operations require only a fraction of a second, and when completed a low humming sound, known as the *dial tone*, is heard by the subscriber. Upon receiving this signal the subscriber dials the number desired, the procedure being the same whether the number desired is in a manual or in a machine switching office. The progress of the call in a general way will be traced with the aid of Fig. 494.

The electrical impulses from the dial come through the line finder and sender-selector to the sender which registers them. These impulses are on a decimal basis, whereas the office

trunks and subscribers' lines are in groups of 500. Therefore the sender must translate the impulses to fit the selecting mechanisms used in the system. The sender automatically causes the particular *district-selector*, which is permanently associated with the line finder, to select an idle trunk to the office of the called subscriber.

The trunk leading to the same or to some other machine-switching office terminates on an *incoming selector;* this selector

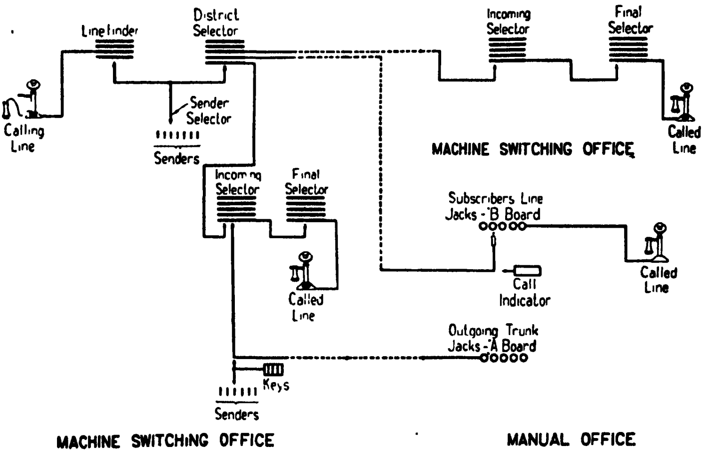


Fig. 494. — Schematic Diagram Showing Connections between Machine-switching and Manual Telephone Offices.

chooses one of a number of other selectors, called *final selectors,* which have access to the subscribers' lines. Since a machine-switching office has a capacity of 10,000 subscribers and each group of final selectors has access to 500 subscribers, 20 groups of final selectors are necessary. Consequently there are 20 groups of trunks on the incoming selector frames, each group leading to a different frame of final selectors. Thus the incoming selector, under control of the sender in the originating office, trips the proper brush, chooses the proper group, and lastly selects an idle trunk leading to a final selector; this selector in turn goes through the same process to locate the

called subscriber's line. Upon establishing the connection, the sender is released and is ready to be used for another call. If the called line is idle, ringing commences and the calling subscriber is made aware of that fact by an audible signal; but if the line is busy, an intermittent buzz, recognized as the busy signal, is sent back to the calling subscriber.

When connection is made with a subscriber joined to a manual office, the call is routed from the district selector to the B-board of the manual office, where the number desired appears before the operator in the form of visible numbers on the keyshelf. This information, together with the number of the trunk on which the call is being handled, enables the operator to complete the connection by inserting the trunk plug into the jack of the subscriber's line. Calls originating in a manual office and intended for subscribers of a machine-switching office may be traced from the figure.

397. Telephone Repeaters. – The three-element vacuum tube (¶ 385) is now largely used on long telephone lines for amplifying the voice currents; it has practically superceded the

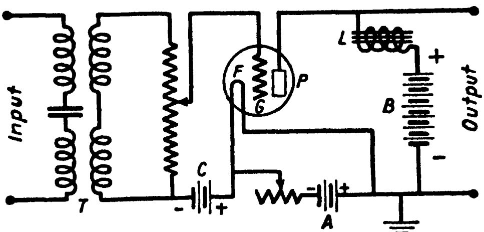


Fig. 495. — Connections of a Vacuum-tube Repeater Element.

so-called mechanical repeater which consisted of a telephone receiver coupled with a transmitter. In the vacuum-tube repeater, the electrical energy to be amplified is applied to the input or grid circuit of the vacuum tube, and the amplified energy is made available in its output or plate circuit. The tube circuits thus constitute a *repeater element* which permits of telephone transmission in one direction.

The connection diagram of such a repeater element is given in Fig. 495. The voltage induced in the secondary winding of the

input transformer T is applied to a high resistance so that a portion of this voltage may be impressed from the filament F to the grid G. The plate circuit of the tube includes the battery B and the choke coil L; the latter confines the voice currents to the output circuit indicated by the terminals at the right. The C-battery maintains the grid negative to prevent a current flowing between the grid and filament.

A simple method of inserting a repeater element into a telephone line in order to secure two-way transmission is indicated in Fig. 496. The input side of the repeater element R is bridged

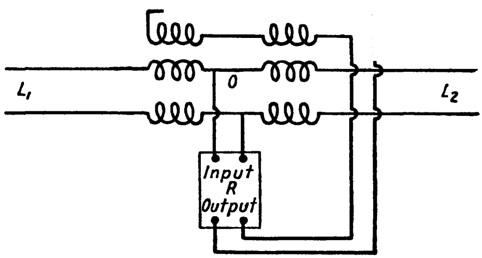


Fig. 496. — Telephone Repeater Set.

across the line, and the output side is connected to a winding of the output transformer O. Energy entering from line section L_1 divides at the repeating station; part is transferred by transformer action to the output circuit of the repeater and is there lost, the other part enters the input circuit and is amplified; no energy is transmitted directly to the line section L_2 if the telephone line is properly proportioned. The amplified energy from the repeater is then supplied to both line sections, but the portion going back to L_1 is not usefully employed.

Another method of introducing a telephone repeater involves a balancing artificial line for each line section, two repeater elements, and two output transformers. This method is used where more than one repeater is required on a line or where two dissimilar lines are to be connected by a repeater.

398. Carrier-Current Transmission. — The principle utilized in radio telephony of modulating a high-frequency wave at the transmitter and rectifying this wave at the receiver, which

process is explained in the next lesson, has been applied with success to telegraphy and telephony over line wires in order to increase the number of channels of communication afforded by a single circuit. This method, sometimes referred to as "wired wireless," is properly termed *carrier-current* communication, since alternating currents of different and relatively-high frequencies are employed to "carry" the signal or speech waves. With this system a single circuit, if traffic demanded, would furnish simultaneously 4 two-way telephone channels, and 20 telegraph channels, 10 in each direction.

While the carrier system is essentially the same for both telegraph and telephone transmission, the following description will be confined to telegraphy for the sake of simplicity. The fundamental features of this type of multiplex operation are: (a) generation of the several high-frequency E. M. F.'s for furnishing the carrier currents, (b) modulating each carrier current to the variations in strength which characterize the telegraph signals, (c) transmitting the modulated carrier waves and amplifying them if necessary by repeaters, (d) separating the several carrier currents at the receiving terminal according to their frequencies by means of selective circuits or *filters*, (e) rectifying the selected carrier currents so as to obtain the original characteristics of the telegraph message.

The carrier currents are generated by vacuum-tube oscillators (¶ 407), which have their frequencies determined by the inductance and capacitance of their associated circuits, or by inductor-type alternators (¶ 363), each consisting of a number of toothed disks driven past the field poles by an electric motor. Modulation in the present carrier telegraph system is accomplished by merely starting and stopping the carrier current with a key or relay contact in accordance with the telegraph signals. Rectification is accomplished by a vacuum-tube detector or rectifier (¶ 415) with a shunt condenser, the resulting direct current being passed through the receiving relay. Thus each key serves to produce variations of intensity of only one carrier current, and these variations are made intelligible by only one of the receiving relays connected to the line.

The selecting circuits or filters, which separate the various frequencies and thus make multiplex operation possible, consist

of inductance coils and condensers of appropriate size and manner of connection so as to transmit certain frequencies or bands of frequencies and to suppress the adjacent frequencies; these are described in ¶ 356. When such filters of different electrical constants are connected in parallel to a common line, a current of particular frequency flowing therein will pass almost entirely

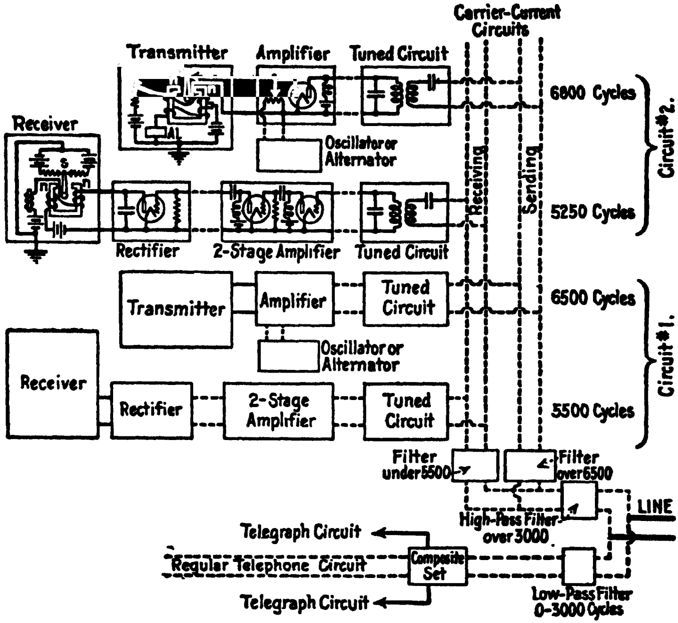


Fig. 497. — Carrier-current Telegraph Circuits.

through the filter for which it is tuned. Selective circuits comprising a number of sections, each containing inductance coils and condensers, can be designed to transmit currents up to a certain frequency with little attenuation and to suppress those of higher frequency, or vice versa; such circuits are called *low-pass filters* and *high-pass filters* respectively.

Fig. 497 gives the schematic diagram of one terminal set of a carrier telegraph system, and shows two duplex channels. At the

bottom are shown the arrangements involving low- and high-pass filters for applying the system to a regular telephone circuit, which also provides two telegraph channels through a so-called composite set. In addition to using tuned circuits at the receiving end, the diagram also shows them at the sending end in order to prevent currents produced at one transmitter from flowing through the circuits of other transmitters. It will be noted that modulation is accomplished by making and breaking a short-circuited connection across the input side of a vacuum-tube amplifier. Polarized relays are used as transmitting and receiving instruments to improve the transmission of signals.

Depression of a key actuates the transmitting relay and removes the short-circuit from the input side of the amplifier; such repeated action permits spurts of carrier-frequency current to pass through the selecting circuit to the line. At the other end of the line the modulated carrier current passes through the appropriate tuned circuit into a two-stage amplifier, and then into a third vacuum tube functioning as a rectifier. When the amplified carrier current reaches this tube the direct current in its plate circuit rises to a definite value and operates the receiving relay. For carrier telegraph operation over a long-distance circuit intermediate telephone repeater sets are used; only one set is needed at each repeating station since it serves to amplify all the carrier currents which the circuit is transmitting.

399. Telephotography. — The transmission of photographs by electricity over electric circuits, called *telephotography*, has been developed to a great extent during recent years. The two fundamental components of a telephotographic system are: a *photoelectric cell*, which produces a varying electric current proportional to the intensities of light incident upon the cell, and a *light-relay*, which retranslates this electric current into light of varying intensities to correspond with the original beam.

A typical photoelectric cell consists of two electrodes in a sealed glass bulb containing argon at low pressure. The cathode is a photo-sensitive material, such as potassium, sodium, rubidium or caesium, which is spread upon the inside wall of the bulb to form a thin layer. The anode is a relatively-small

metallic ring supported in the neighborhood of the alkali layer These electrodes are brought to the exterior by sealed-in wires, and are shown in Fig. 498 connected to a battery B and galvanometer G. When light passes through the window W and strikes the cathode film, electrons are released from its surface and an electric current is caused to flow instantly in the space between the cathode C and anode A, which current may be measured by the galvanometer. Experiment shows that the galvanometer readings are proportional to the intensities of the incident light, provided there are no free glass surfaces on which electric charges may accumulate. Photoelectric cells for picture transmission are made of pyrex glass and employ potassium; they have the shape shown in the figure, the long neck providing insulation between the electrodes for the avoidance of leakage. With −100 volts on the potassium electrode the current is about 2 microamperes.

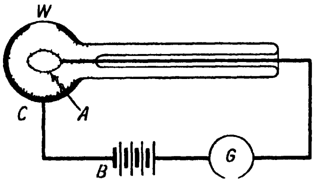


Fig. 498. — Photoelectric Cell.
Total length is 9 inches, bulb diameter is 1 1/2 inches

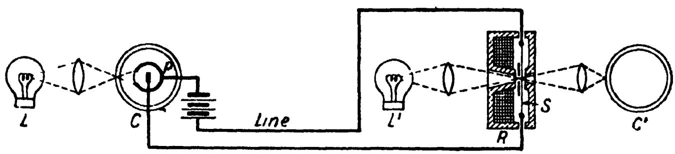


Fig. 499. — Method of Transmitting Pictures by Wire.

The light-relay consists of an electromagnet having an aperture in its core to allow the passage of light, and a thin strip of metal supported in the magnetic field so as to entirely cover the aperture. When the direct current from the photoelectric cell flows through the strip, it is deflected to one side, exposing the aperture, and permitting a beam of light to pass through which is proportional to the current strength.

Fig. 499 illustrates the method of sending pictures over a line circuit. The picture to be transmitted is prepared as a film

transparency which is bent into the form of a cylinder. When this cylinder C rotates, and at the same time advances axially by means of a screw, every element of the picture is illuminated in turn by lamp L, and the quantity of light transmitted through the film is received by the photoelectric cell P The varying current set up by this cell is transmitted over the line to the light-relay R. Its conducting strip S will be deflected and vary the light (from lamp L′) which may fall upon the photographically-sensitive film wrapped around cylinder C′ Thus the film will be exposed from point to point by amounts varying in proportion to the light and shade of the original picture. Obviously the two cylinders must revolve in synchronism.

Since ordinary telephone lines are not well suited for the transmission of weak direct currents, the photoelectric current is first amplified by means of vacuum tubes and then used to modulate a carrier wave. As the carrier current, modulated in accordance with the lights and shades of the picture under transmission, passes through the light-relay, the strip will open and close the light aperture with each pulse of the alternating current, but the envelope of these pulses will follow the lights and shades of the original picture. The current for synchronizing the two cylinders is sent over the same line circuit by utilizing a carrier channel of lower frequency; the synchronizing carrier current being separated by filters from the photoelectric carrier current. Picture transmission may also be accomplished by radio, the carrier currents being then of radio frequency.

QUESTIONS

1. What is the difference between a sounder and a relay?
2. Draw the circuit of a single Morse telegraph line and explain its operation.
3. How far would it be possible to telegraph over a line having 5 ohms resistance per mile of length and having a 120-volt battery at each end? There are ten 150-ohm relays on the circuit, each requiring 0.05 ampere for actuation. *Ans.* 660 miles.
4. Explain the operation of a simplex or single Morse repeater.
5. What is an artificial line and why is it used on duplex and quadruplex telegraph lines?
6. Make a diagram to show how two messages may be sent in opposite directions over a single wire without interfering with each other.

7. How is quadruplex transmission attained?

8. Distinguish between the synchronous and carrier-current methods of multiplex telegraphy.

9. Describe the method of sending telegraph messages by tape transmitters and receiving them as printed letters.

10. Describe the telephone transmitter and receiver.

11. What is the purpose of an induction coil in a subscriber's telephone set?

12. Sketch the connections of a bridging-magneto and of a common-battery subscriber's set.

13. Trace the establishment of a connection at the A-board between two subscribers of a common-battery telephone system.

14. How is a call from a subscriber of a manual telephone central office completed to a subscriber of a machine-switching office?

15. Show by a diagram how a repeater element is inserted into a telephone line in order to secure two-way telephonic transmission.

16. What is a photoelectric cell?

17. How are photographs transmitted electrically?

LESSON XXXIII

RADIO TRANSMISSION

Electromagnetic Waves — Table XXIII — The Production of Electromagnetic Waves — Frequency, Oscillation Constant and Wave Length — Damped Waves and Continuous Waves — Types of Antennas — Methods of Exciting the Antenna Circuit — Table XXIV — Continuous-Wave Transmission Systems — The Vacuum-Tube Oscillator — The Vacuum-Tube Telegraph Transmitter — The Vacuum-Tube Telephone Transmitter — The Heising System of Modulation — Frequency Control of Oscillators — How the Waves Leave the Transmitting Antenna — Questions.

400. Electromagnetic Waves. — Any alternating current causes the *radiation* in all directions of electromagnetic energy into space in the form of *electromagnetic waves*. In fact, any electrical disturbance, as for instance, a change in the current strength in a conductor, causes some radiation of electromagnetic energy. By making the frequency of an alternating current very great as compared with the frequencies commonly employed in electric lighting and power circuits, it is possible to radiate electromagnetic energy in all directions, and for great distances, from the conductor carrying this *high-frequency* current, although the radiation may be greater in some directions than in others. It is possible to *detect* the presence of this energy by means of suitable apparatus affected by it and remotely situated from the source of energy.

This simple principle of the radiation of electromagnetic energy through space and the detection of its presence forms the basic principle employed in systems of *radio telegraphy* and *radio telephony*. In simple systems of radio telegraphy, the radiation of electromagnetic energy into space from the transmitting station is controlled by means of a telegraph key in the usual manner so as to form dots and dashes. The *International Code* is used universally. In systems of radio telephony, energy is radiated continuously from the transmitting station while

speaking. The effect of the voice in the telephone transmitter is to vary or *modulate* the radiation of energy, in the form of electromagnetic waves, from the transmitting station, without changing the continuity or the frequency of the waves.

The propagation of electromagnetic energy through space is accomplished through the hypothetical *ether*, regarding which little is known, but light, heat and other electromagnetic disturbances, in the form of electromagnetic waves, are propagated through it at the rate of 300,000,000 meters (approximately

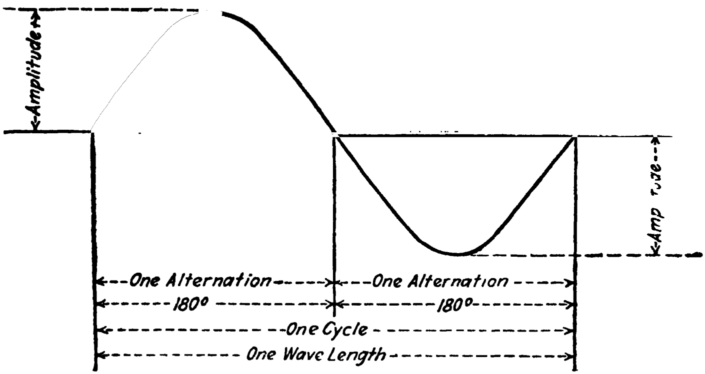


Fig 500 — Sine Wave of Alternating Current.

186,500 miles) per second. The ether is assumed to occupy all space regardless of the presence of matter, since the particles constituting the structures of matter are very widely separated as compared with the space which they individually occupy. Any electric current produces in the ether interlinked magnetic and electrostatic fields at right angles to each other. When any alternating current is reversing, the magnetic and static fields change correspondingly and some of the energy is propagated through the ether at the rate of 300,000,000 meters per second. If the frequency of this current was 300,000,000 cycles per second, the energy would travel only one meter by the time that one complete cycle had taken place. Therefore, the *wave length* would be one meter with a frequency of 300,000,000 cycles per second.

Fig. 500 illustrates a sine wave form which is generally assumed in radio calculations; this is identical with that shown in Fig. 388. It has the general shape of water waves, but the electromagnetic waves radiated from a radio transmitting station travel in all directions and, therefore, are greatly different from water waves which travel only in one plane. Electromagnetic waves travel through space whether or not this space is occupied by any other substance such as air, gas or wood, although not so well as through the ether alone; but they act on electric conductors in such a manner as to tend to produce high-frequency alternating currents in such conductors. Hence, the energy of the electromagnetic waves may be converted into electric energy in such conductors, and this is the principle of the reception of radio signals.

The phenomenon of light is a manifestation of the presence of electromagnetic waves of exceedingly high frequencies as compared with *radio frequencies*, yet light travels from the heated filament of an incandescent lamp through the vacuum (ether) between the filament and the glass bulb, through the glass and air surrounding it, and, impinging upon the optic nerve, produces the sensation of light. The presence of the glass bulb and the air surrounding it is a detriment rather than a benefit, and these have no functions whatsoever in the propagation of the electromagnetic waves (called *light waves* in this case). In this illustration an incandescent lamp serves as a transmitter and the eye as a receiver. In fact, naval vessels are equipped with so-called "blinkers" which operate on this principle, by using the International Code.

Wave lengths corresponding to various radio frequencies are computed by dividing 300,000,000 meters per second (the velocity of propagation) by the frequencies in cycles per second, or wave length in meters $= \frac{300{,}000{,}000 \text{ meters per second}}{\text{frequency in cycles per second}}$. The Greek letter λ (lambda) is used to represent the wave length, v the velocity of propagation, and f the frequency in cycles per second. Therefore, the foregoing equation may be written

$$\lambda = \frac{v}{f} \quad \ldots\ldots\ldots \quad (156).$$

Also $$f = \frac{v}{\lambda} \quad \ldots\ldots\ldots \quad (157).$$

Table XXIII. Wave Lengths Corresponding to Various Frequencies

Frequency in cycles per second	Wave length in meters	Frequency in cycles per second	Wave length in meters
300,000,000	1	300,000	1,000
30,000,000	10	100,000	3,000
3,000,000	100	50,000	6,000
1,000,000	300	30,000	10,000
500,000	600	20,000	15,000

In general, passenger steamships operate radio apparatus on wave lengths varying from 600 to 900 meters, while the wave lengths of some of the large land stations vary from 13 meters to 20,000 meters. By *tuning* the circuits of radio receiving sets it is possible to cause them to respond only to a given wave length. Then, although there may be many stations sending messages at other wave lengths, practically no *interference* will result as all other wave lengths are "tuned out." A certain amount of interference may result when the transmitting or the receiving apparatus does not tune sharply.

401. The Production of Electromagnetic Waves. — An *antenna* may be considered broadly as a lightning rod, cut apart near the ground, with radio apparatus connected therein.[1] When an alternator is connected in series with a grounded antenna, the alternating E. M. F. alternately forces electricity up the wire, away from the ground, and down the wire towards the ground. Therefore, there is a difference of potential between the ground and the wire when an E. M. F. is impressed upon them by the alternator. In this way, the wire and ground act like the opposite plates of a condenser.

All antenna circuits contain both the properties *inductance* (¶ 268) and *capacitance* (¶ 342). The inductance has a retarding

[1] Benjamin Franklin made the first *receiving* antenna, using his body as a *detector*, in connection with the key attached to the moistened string leading to his kite, and making connection with the ground by standing upon it.

effect on the motion of electricity, while capacitance tends to accelerate its motion. An analogy of the antenna is found in the tuning fork used by musicians. Owing to the "springiness" of the steel, the tuning fork always tends to maintain a fixed shape, but when a prong is struck a sharp blow it is displaced from its normal position and tends instantly to resume that position. However, the inertia of the prong prevents it from instantly flying back, but its velocity increases as the prong approaches its normal position, so that when the prong does reach that position, its velocity is a maximum. Then the inertia of the prong causes it to keep on going beyond its normal position, thus displacing it as before, but in the opposite direction. When the kinetic energy (motional energy) is all converted into potential (static) energy, the prong starts towards its normal position again; and so it swings or oscillates to and fro until all of the energy has been radiated away in the form of sound waves, or has been converted into heat. Comparing this fork with an electric circuit, it appears that capacitance may be called the "electric springiness," and inductance the "electric inertia" of a circuit. Through the combined effects of inductance and capacitance the electricity in an antenna is made to oscillate to and fro when given an "electric blow," as in short-wave spark sets, or when set into continuous oscillation by some device like an alternator, operating in tune with the circuit; this oscillation causes electromagnetic waves to be radiated throughout space.

402. Frequency, Oscillation Constant and Wave Length. — The natural frequency of the oscillating circuit is increased when either the inductance or the capacitance is decreased, and *vice versa*. If either one of these constants be increased and the other decreased so that their product remains unchanged, then the frequency of the circuit will remain the same. These facts can be put in the form of an equation by letting L be the inductance in henrys (¶ 336) and C be the capacitance in farads (¶ 342); then the natural frequency in cycles per second is given by

$$f = \frac{1}{\sqrt{\text{[illegible]}}}, \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(158)}.$$

where $\pi = 3.1416$, and where the square root of the product of the inductance and capacitance is called the *oscillation constant.* In radio practice the units of inductance and capacitance above mentioned are unduly large, and for convenience the *millihenry* [1] (= one-thousandth of a henry) and the *microfarad* (= one-millionth of a farad) are used instead. With these units Formula (158) becomes

$$f = \frac{5033}{\sqrt{L \times C}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(159)}.$$

The wave length can be expressed in terms of the oscillation constant by equating Formula (157), namely

$$f = \frac{v}{\lambda} = \frac{300{,}000{,}000}{\lambda},$$

with Equation (158); thus,

$$\frac{300{,}000{,}000}{\lambda} = \frac{1}{2\pi\sqrt{LC}},$$

whence

$$\lambda = 1{,}885{,}000{,}000\,\sqrt{LC} \text{ meters} \quad . \; . \; . \; . \; . \quad \textbf{(160)}.$$

Transposing Formula (160), the oscillation constant becomes

$$\sqrt{LC} = \frac{\lambda}{1{,}885{,}000{,}000} \quad . \; . \; . \; . \; . \; . \; . \quad \textbf{(161)}.$$

Problem 157. — The oscillation constant of a circuit is 0.000003183. Find the wave length

By Formula (160) $\lambda = 1{,}885{,}000{,}000 \times 0.000003183 = 6000$ meters.

Problem 158. — A circuit has a capacitance of 0.0012 microfarad. What should its inductance be in order to have a wave length of 600 meters?

From Table XXIII (¶ 400) the frequency is 500,000 cycles for a wave length of 600 meters; therefore from Formula (159)

$$\sqrt{L \times C} = \frac{5033}{500{,}000} = 0.01006.$$

Then $$L \times C = 0.01006 \times 0.01006 = 0.0001012$$

or, since $C = 0.0012$ microfarad,

$$L = \frac{0.0001012}{0.0012} = 0.0843 \text{ millihenry}.$$

[1] The *centimeter* is another unit of inductance much used. One million centimeters equal one millihenry.

403. Damped Waves and Continuous Waves. — A *damped-wave* radio transmitting set behaves very much like a tuning fork or a bell, only electromagnetic waves are radiated from it

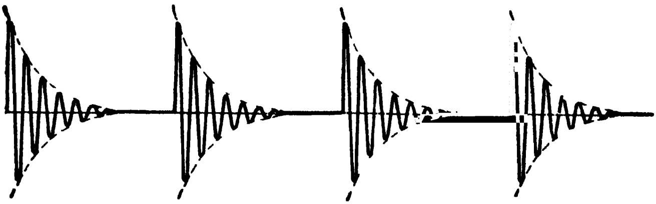


Fig 501 — Damped Wave Trains.
Produced by spark radio sets

into space instead of sound waves into the air. A sharp "electrical blow" is struck, and then the electricity in the antenna circuit vibrates to and fro or oscillates at the natural frequency of the circuit, and the energy of the blow is quickly dissipated, part being radiated away into space, and the remainder converted into heat in the antenna circuit due to its resistance (see I^2R loss, ¶ 237). Therefore, if a series of "electrical blows" is given the electricity in the antenna circuit in such an order of succession that a blow shall be struck just as the effect of the preceding blow dies out, a series of groups of constantly decreasing waves will result which can be represented graphically as in Fig. 501 Such a *wave train* is said to consist of *damped waves*.

On the other hand, if the antenna circuit is struck "electrical blows" in such a rapid order of succession that the circuit will continue to vibrate continuously and harmoniously, as when a high-frequency alternator supplies energy to the antenna circuit at the natural frequency of the antenna circuit, then an "undamped" or *continuous-wave* train will result, as depicted in Fig. 502. Damped waves are characteristic of "spark" telegraph transmitting sets, while continuous waves are em-

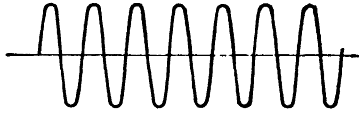


Fig. 502. — Undamped or Continuous Waves.

ployed in radio telephone transmitting sets, as well as in continuous-wave telegraph transmitting sets.

404. Types of Antennas. — The term *antenna* will be used to signify the entire radiating or receiving system. In Fig. 503, the *aerial* is the wire, or group of wires connected in parallel, strung between masts or other supports and insulated therefrom. The *counterpoise* may be a wire screen, perhaps of "chicken wire," or it may be similar to the aerial, and is either suspended slightly above the ground, laid upon the ground, or may be the ground itself if there is sufficient moisture to make the ground a good conductor. On ships, metal parts, such as a steel hull, form the counterpoise; in this case the water acts as part of the counterpoise. In airplanes, the aerial trails behind the airplane, and the engine, stays, etc., either collectively or individually, form the counterpoise. The greater part of the inductance of the antenna system is usually contained within the radio set itself.

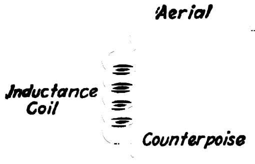


Fig. 503. — Elements of a Radio Antenna.

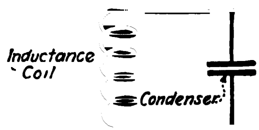


Fig. 504. — Electrical Equivalent of a Radio Antenna.

The aerial and counterpoise, then, while possessing some inductance, really form the capacitance part of the antenna circuit and are the equivalents of the two plates of a condenser. Fig. 504 shows a circuit with inductance and capacitance connected in series, and is the electrical equivalent of Fig. 503, with the exception that a condenser of small size is used instead of an aerial and a counterpoise, although the capacitance of the former may be equal to that of the latter. When the circuit is struck an "electrical blow," an E. M. F. will be induced in it which will cause an electric current to oscillate therein, but the arrangement

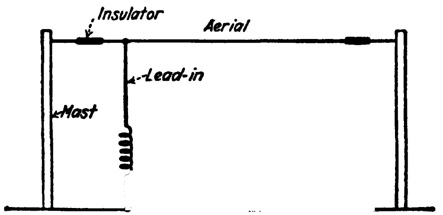


Fig. 505. — L-type Aerial.

shown in Fig. 503 will radiate electromagnetic waves to a comparatively great extent, while the compact arrangement shown in Fig. 504 will radiate only over a restricted range. The condenser should be extended in size in order to obtain good radiation.

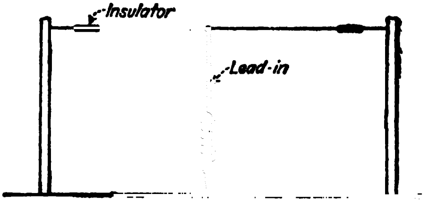


Fig. 506. — T-type Aerial.

The principal types of aerials are the " L," " T," " V," and " Umbrella " types. The reasons for these names will be apparent by referring to Figs. 505 to 508 inclusive. In all cases, the *lead-in* wire is the wire connecting the aerial with the inductance. All of these aerials, with the single exception of the umbrella type, possess what is known as the *directional effect*, which means that energy is transmitted and received better in certain directions than in others. The umbrella type functions equally well in all directions, while, in the other types, the directional effect is best in the direction of the lead-in wire. Therefore, the apex of the " V," for instance, always should be pointed towards the distant station in order to obtain the best results, although communication can be obtained from all other direc-

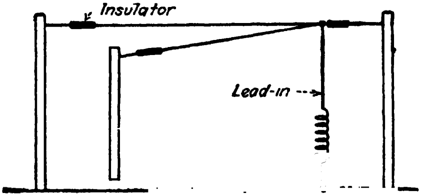


Fig. 507. — V-type Aerial.

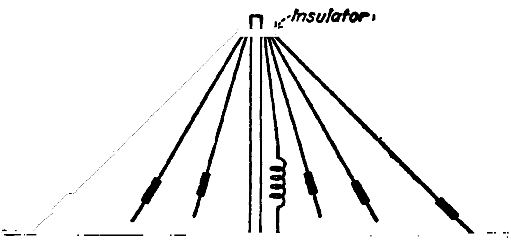


Fig. 508 — Umbrella-type Aerial.

tions. In the T-type aerial, equally good results can be obtained from directions at the right or left of the lead-in wire, when viewed as in Fig. 506. The directional properties just mentioned apply only to aerials in which the length of the top portion is 20 or more times the length of the lead-in.

A general rule for the total length of T or L aerials is to make them approximately $\frac{2}{9}$ of the wave length for transmitting stations. In other words, the wave length will be approximately 4.5 times the length of the aerial wire. For receiving stations, the length of the antenna usually is not so important a matter.

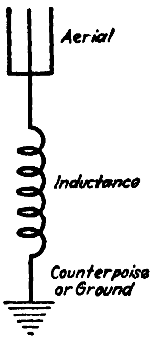


Fig. 509. — Diagrammatic Representation of an Antenna Circuit.

All antennas possess *natural wave lengths*, owing to their inductances and capacitances. Some inductance always is added to the antenna circuit in order that the antenna may be tuned to a given wave length, or to a series of given wave lengths, and to provide means for *coupling* the aerial with the radio apparatus. The proper wave length for a transmitting antenna may be found by exciting the antenna circuit and, with a hot-wire ammeter connected in the antenna circuit, adjusting the inductance until the maximum current strength is obtained. For a given input, the antenna is then radiating the maximum amount of energy. Sometimes a condenser is connected in series with the antenna circuit for decreasing the wave length of the antenna; this is called a *short-wave condenser*.

All parts of a transmitting antenna must be thoroughly insulated from each other and widely separated so that sparks cannot jump from one part to another. Since receiving antennas are subject to very slight electrical strains, the matter of insulation is not so important excepting that precautions should be taken so that no leakage, as through water or moisture, will result. The lead-in and the ground or counterpoise wire should be widely separated to prevent capacitance effects and absorption. In some installations the same antenna is used for both transmitting and receiving purposes. In connection diagrams the antenna circuit will generally be represented as in Fig. 509.

405. Methods of Exciting the Antenna Circuit. — There are two general methods employed for exciting the antenna circuit, known as the *direct*, and the *indirect* excitation transmission systems. The simplest method of directly exciting the antenna circuit would be to connect the armature of a high-frequency alternator in series with the antenna circuit, as in Fig. 510. In such an arrangement, the alternator is operated at a speed such that its frequency is the same as the natural frequency of the antenna circuit. These machines are by no means simple alternators and must be run at very high speeds; however, they produce continuous waves and, therefore, cause the radiation of the maximum amount of energy. Such alternators are employed in a few large radio stations.

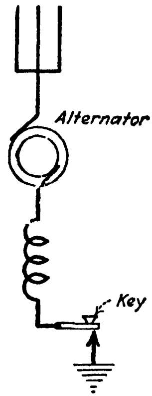


Fig. 510. — Direct Excitation of Antenna.

In the ordinary *spark sets*, the antenna is alternately excited, or struck an "electrical blow," and then left to oscillate at its natural frequency, thus producing damped waves since the resistance of the antenna circuit causes the conversion of some of the energy into heat. A simple representation of this method is illustrated in Fig. 511. With the alternator revolving constantly, when the key is depressed an alternating current with a frequency of, say, 500 cycles per second, flows through the primary of a transformer which raises the E. M. F. up to, say, 20,000 volts (maximum value of wave) on the secondary side. This E. M. F. is sufficient to break down or puncture the air in the *spark gap* 1000 times per second, since the E. M. F. reaches its maximum value during each alternation, or twice per cycle. When

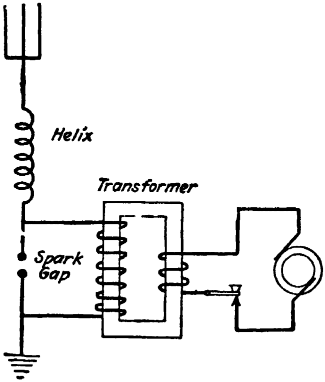


Fig. 511. — Elements of a Spark Radio Set.

a spark passes, the secondary of the transformer is practically short-circuited owing to the fairly good conducting path of the spark, and the antenna then oscillates at its natural frequency of thousands of cycles per second for each time that the gap has been broken down by the 500-cycle E. M. F. The energy is quickly damped out after each breakdown due to the radiation of energy in the form of electromagnetic waves, the heat developed in the spark, and the heat developed in the wires of the antenna circuit, before the exciting E. M. F. of the transformer again attains its maximum. The

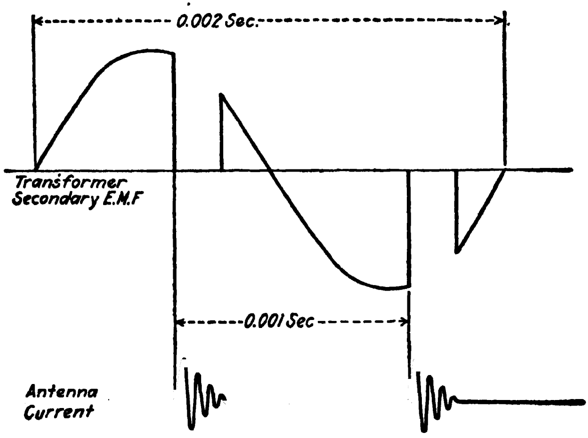


Fig. 512. — Production of Oscillations by Spark Sets.
The antenna current has a much greater frequency than the current in the transformer that excites the antenna.

radiated waves during each breakdown make up one wave train Fig. 512 shows the relation between the low-frequency E. M. F. in the secondary of the transformer which produces the sparks, and the high-frequency current in the antenna circuit. There is an antenna current only during the periods that the gap is bridged by a spark.

The *logarithmic decrement* is a measure of the time rate of decay of damped waves. Its value is expressed by the logarithm (to base $\epsilon = 2.718$) of the ratio of two successive amplitudes

of the wave train in the same direction; the logarithmic decrement is given by the equation

$$\delta = \log_\epsilon \frac{a}{b}, \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad \textbf{(162)}.$$

where a and b are two successive amplitudes of the wave train. This can be expressed in terms of ordinary logarithms (*i.e.* to base 10) by the formula

$$\delta = 2.303 \log_{10} \frac{a}{b} \quad . \ . \ . \ . \ . \ . \quad \textbf{(163)}.$$

In 1912 the U. S. Government, in order to limit interference of radio stations with each other, adopted a law which, among other provisions, required that the logarithmic decrement of the waves radiated from a transmitter shall not exceed 0.2.

The significance of logarithms is briefly as follows: Ten squared is $10 \times 10 = 100$, and therefore 100 is said to be the *second power* of 10; likewise 1000 is the third power of 10 and, of course, 10 is the first power of 10. In the same manner any number may be considered as being a power of ten. The numbers lying between 10 and 100 will be somewhere between the first and second powers of ten. Those numbers between 100 and 1000 will be more than the second power of ten and less than the third power. Tables have been prepared that show the power of ten which will raise it to any given number. Thus 10^1 equals 10; whence the *logarithm* of 10 to the *base* 10 is 1. Similarly, the logarithm of 100 is 2, and the logarithm of 1000 is 3. The logarithm of 45 is greater than 1 and less than 2; from a table of logarithms, its value is found to be 1.653, or $10^{1.653}$ equals 45. This system of logarithms which uses 10 for a base is called the *common* or *Briggs* system of logarithms; a short table of these is given in Table XXIV.

It is not necessary to use 10 as the base of logarithms; any number may be chosen as the base for a system, 3 for example. With 3 as a base, the logarithm of 9 would be 2, log 27 would be 3, log 81 would be 4, and so on, for 9 is the second power of 3, 27 is the third power of 3, and 81 is the

Table XXIV. Logarithms to Base 10

1.0	0	5	0.699	13	1.114	45	1.653
1.1	0.041	6	0.778	14	1.146	50	1.699
1.2	0.079	7	0.845	15	1.176	55	1.740
1.4	0.146	8	0.903	20	1.301	60	1.778
1.7	0.230	9	0.954	25	1.398	70	1.845
2.0	0.301	10	1.000	30	1.477	80	1.903
3.0	0.477	11	1.041	35	1.544	90	1.954
4.0	0.602	12	1.079	40	1.602	100	2.000

fourth power of 3. The base of the so-called *natural* or *Napierian* system of logarithms is 2.718. In other words, all numbers instead of being considered as certain powers of 10 as in the common system of logarithms are represented as powers of 2.718; this number is referred to as ϵ (epsilon).

Problem 159. — The successive amplitudes of a damped wave train are 10, 9.0, 8.1, 7.3, etc. Find the logarithmic decrement of the waves.

The ratio of two successive amplitudes is $\frac{10}{9} = 1.11$, $\frac{9.0}{8.1} = 1.11$, $\frac{8.1}{7.3} = 1.11$; thus $\frac{a}{b}$ has the constant value of 1.11.

The logarithm to base 10 of 1.11 is approximately 0.041, therefore the logarithmic decrement from Formula (163) is $\delta = 2.303 \log_{10} 1.11 = 2.303 \times 0.041 = 0.094$.

The resistance, inductance and capacitance of a circuit all affect the logarithmic decrement, as given by the formula

$$\delta = \pi R \sqrt{\frac{C}{L}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (164).$$

This formula is strictly applicable only to those circuits which are non-radiative, but if R represents the total resistance of the antenna circuit, *ohmic* and *radiation* resistance, the formula is accurate. From this formula, it will be seen that the greater the resistance and capacitance of a circuit and the less the inductance, the greater will be the damping or the decrement of the circuit. In order, then, to produce feeble damping of the current in the antenna circuit and hence feeble damping of the electrical waves which it radiates, the circuit should have large inductance and low values of resistance and capacitance

Problem 160.—What is the logarithmic decrement of a ship antenna which has 5 ohms resistance, 0.07 millihenry inductance and 0.0009 microfarad capacitance?

By formula (164),

$$\delta = 3.1416 \times 5 \sqrt{\frac{0.0000000009}{0.00007}} = 15.7 \times 0.00359 = 0.0564.$$

Before the spark occurs, energy from the transformer is stored between the aerial and the counterpoise, or ground; these acting like the two plates of a condenser. When the E. M. F. becomes so great that a spark passes, due to electricity being forced across the spark gap, this energy is released and the electricity oscillates at a high frequency to and fro

across the gap and through the *helix* of wire in the antenna circuit which is placed there to provide sufficient inductance in a compact manner. The capacitance of the antenna, between the aerial and the counterpoise, and the inductance of the helix determine the wave length of the antenna. In some spark transmission systems, an induction coil (¶ 270) is used instead of an alternator and transformer, and is operated from a direct-current circuit. The methods above described are all *direct excitation transmission* systems.

In *indirect excitation transmission* systems, there is no spark gap in the antenna circuit, but the spark gap is placed in an

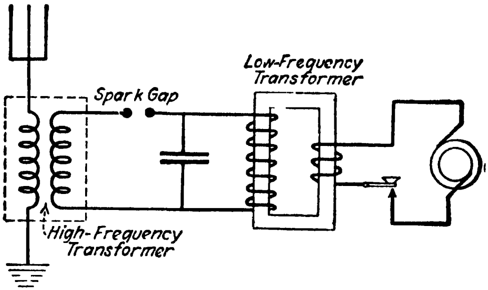


Fig. 513. — Coupled-circuit Spark Set.

oscillating circuit *coupled* with the antenna circuit, as in Fig. 513. The coupling is accomplished by means of a *high-frequency* or *oscillation transformer*, which consists of two helices or inductance coils placed one inside the other, or end to end. High-frequency inductance coils and transformers have *air cores*.

Two circuits are said to be coupled when energy from one circuit can be transferred to the other circuit. For instance, an oscillating circuit containing an inductance coil may be coupled with an antenna in which another inductance coil is inserted, by placing the coils, one over the other, or end to end, so that the varying magnetic flux developed by the oscillating current in one of the inductance coils shall interlink with the turns of wire in the inductance coil of the other circuit. The ratio between the E. M. F. induced in one of the coils and the time rate of change in the current strength in the other coil (which

produces the varying magnetic flux to induce that E. M. F.) is called the *mutual inductance* of the two coils. Two circuits are said to be *loose-coupled* when the mutual inductance is of low value, as when the coils are not very near to each other, and *close-coupled* when the mutual inductance is relatively great. Sharp tuning is obtained with loose coupling.

In the *direct excitation* transmission system shown in Fig. 511, the oscillations are damped by the resistance of the spark. In the indirect excitation transmission system shown in Fig. 513, there is not so much damping in the antenna circuit on account of its low resistance, and the oscillations continue in the antenna circuit after the spark has ceased in the *tuned* coupled circuit.

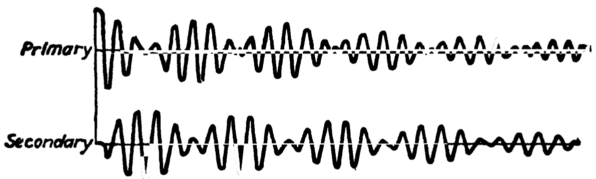


Fig. 514. — Transfer of Energy in Coupled Circuits.

The curves show the currents in the primary and secondary windings of the oscillation transformer. At the moment when the current in one coil oscillates over its maximum range, the current in the other coil almost ceases.

In indirect excitation transmission systems, it is important that the product of the inductance and capacitance in the antenna circuit and the product of the inductance and capacitance in the coupled oscillating circuit shall be equal, as then the circuits are in tune with each other, both having the same wave length.

A *quenched spark* is one which is quickly extinguished after it has "struck." In connection with the indirect excitation transmission, a quenched spark has the advantage of giving the antenna circuit (through the coupled circuit) a sharp "electrical blow," and then permitting the electricity in the antenna circuit to oscillate freely at the natural frequency of the antenna circuit without transferring energy from the antenna circuit through the coupling back to the oscillation circuit, which results when the spark is not quickly extinguished. A *quenched spark gap* consists of a number of metal disks insulated from each other by means of mica washers, thus forming

a chain of short spark gaps connected in series, and with sufficient masses of metal to prevent detrimental heating which would encourage the ionization of gases and prolong the duration of the spark. Some spark gaps are water-cooled in order that the spark may be more quickly extinguished. A similar effect is approximated by the use of a toothed wheel which, running in synchronism with the alternator, permits a spark to pass only when a tooth is opposite the stationary electrode of the spark gap.

Fig. 514 illustrates how energy is transferred from the coupled oscillating circuit to the antenna circuit and then back again when "long" or "ordinary" spark gaps are used, while Fig. 515

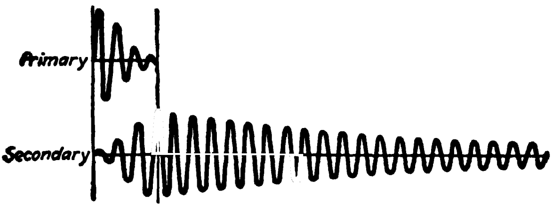


Fig. 515. — Oscillations in the Gap and Antenna Circuits of a Quenched-gap Transmitter.

The current in the primary or gap circuit is highly damped; this permits the antenna or secondary circuit to radiate its energy with feeble damping

shows the effect of a quenched, or "short," spark in acting only long enough to get the electricity in the antenna circuit oscillating properly, and then to cease altogether so as not to interfere with the oscillations in the antenna circuit.

406. Continuous-Wave Transmission Systems. — Continuous electric oscillations are produced by high-frequency alternators, electric arcs, and vacuum tubes. The alternator method has been touched upon in the last paragraph in connection with Fig. 510. If the key is held down, the alternator will produce continuous electric oscillations of equal amplitude in the antenna circuit, and a continuous-wave train will be radiated into space.

An *arc transmission* system is illustrated in Fig. 516. The electric arc is fed by a direct-current generator through a choke coil and a resistance. When the current in the arc increases,

the voltage across it decreases, and *vice versa*. When the current first begins to flow through the arc, the condenser in the oscillating circuit at the left in Fig. 516 is charged and, being connected in shunt with the arc, diverts some current from the arc, which causes the E. M. F. across the arc to increase and thus further charge the condenser, until the E. M. F. of the condenser is equal to that of the arc. However, the inductance in series with the condenser in the oscillating circuit possesses the property of "electric inertia," so that the electricity keeps on flowing and charges the condenser to a higher E. M. F. than that of the arc. Then the condenser commences to discharge through the arc, in the opposite direction, much as it

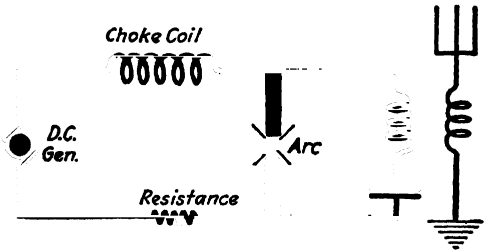


Fig. 516. — Direct-current Arc Transmitter.

would discharge through a spark gap, and this causes a diminution in the arc voltage which permits the condenser to further discharge. On account of inductance, the electricity keeps on flowing until the E. M. F. of the condenser is less than that of the arc. Then the condenser again begins to charge, and the cycle is completed. The result is a high-frequency current in the circuit shunted around the arc in Fig. 516, and continuous oscillations are imparted to the antenna circuit by means of the coupling. The choke coil prevents high-frequency currents from flowing in the generating circuit, and the resistance limits the current strength in the entire system, which is necessitated by the negative resistance coefficient of the arc.

407. The Vacuum-Tube Oscillator. — The three-element vacuum tube, described in ¶ 385, can be used to generate electrical oscillations when the plate and grid circuits are coupled so that some energy in the plate circuit is fed back to the grid

circuit. Fig. 517 shows the circuit of a simple but effective vacuum-tube oscillator. The frequency of the oscillations generated by this device depends almost entirely upon the constants of the tuned circuit, namely: the inductance L of the coil ab and the capacitance C of the variable condenser. The frequency can be expressed with considerable accuracy by equations (158) or (159). The deviation of the actual frequency from the value given by the equations is due to the fact that the capacitance and inductance of the circuit and tube are not concentrated but are distributed.

To explain the operation of the circuit of Fig. 517, consider the instant when the filament and plate circuits are closed. Electrons will flow from the filament to the plate, establishing a current in the plate circuit and developing a magnetic field in the right-hand portion of the inductance coil. This field about L_2 cuts the turns of L_1, inducing a voltage in the left-hand portion of the coil, exactly as in the transformer. The momentary direction of the counter electromotive force in L_2 is such as to make the intermediate point O positive with respect to b. Similarly the voltage induced in L_1 will be such as to make point a positive with respect to O, and therefore positive to b also. Thus, as the current in the plate circuit grows, it is aided by the positive voltage pulse imparted to the grid G by L_1 (see ¶ 386). However, as the plate current ceases to rise in value, that is, as the plate-circuit current approaches saturation, the voltage induced in L_1 diminishes to zero. Under these conditions the plate-circuit current must decrease because the positive potential which was available at the grid is now lacking. As the plate current falls in value, the potential induced in L_1 is reversed in direction and increased in magnitude. This reversal of the voltage across L_1 aids the reduction of the plate current until

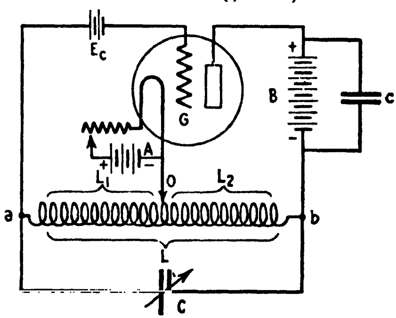


Fig. 517. — Vacuum-tube Oscillator.

it reaches zero. When this value is attained the voltage induced in L_1 is again zero and the plate current begins to rise because the negative grid potential necessary to maintain zero plate current no longer exists. Once more the current rises in the plate circuit and produces a voltage in L_1 directed to make G positive; thus aiding the current to grow, which growth continues until saturation is reached. Thereafter this cycle of events is repeated. Fig. 518 shows the ideal relation between the plate-circuit current and the grid voltage in an oscillator when operating steadily.

As was stated previously, the capacitance of condenser C together with the inductance of coil L (Fig. 517) controls the frequency of the oscillations generated. The filament connection at point O is adjustable so that the best relation of L_1 to L_2 may be found. Condenser c is a by-pass around the B-battery for the high-frequency pulses to the plate. The battery E_c is a desirable addition to the circuit but is not always necessary. It is used to reduce the losses in the grid circuit and thereby to aid oscillation.

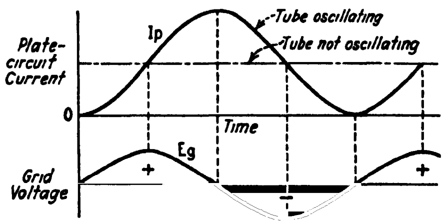


Fig. 518. — Steady-state Plate Current and Grid Voltage Relations in a Vacuum Tube.

408. The Vacuum-Tube Telegraph Transmitter. — It was shown in the foregoing section that if a vacuum tube is connected to an oscillatory circuit in which the plate and grid are properly coupled, continuous and controllable oscillations may be established. These oscillations are transferred to an antenna through a coupling device, such as coils or condensers, and energy is radiated. There remains to be shown how the dots and dashes of a code for the transmission of intelligence are formed.

Fig. 519 illustrates various types of oscillators which are differently coupled to antennas. In the radio telegraph transmitter depicted at (*a*) the x-marks show suitable points for the introduction of a transmitting key. Its function is to interrupt the wave train transmitted into short and long series of cycles to simulate dots and dashes respectively. However, as will

be shown in the next lesson, this method of transmission does not produce audible signals in receivers using crystal or non-oscillating vacuum-tube detectors. For this reason an audible frequency, usually of from 500 to 1000 cycles per second, is impressed by means of a buzzer, tuning-fork, or other device, either upon the grid or upon the antenna circuit of the oscillator. This arrangement modulates the radiated wave so that the signals will be audible with all systems of reception. A radio telegraph transmitter of this type, known as an interrupted continuous wave (I.C.W.) transmitter, is shown in Fig. 519 (*b*).

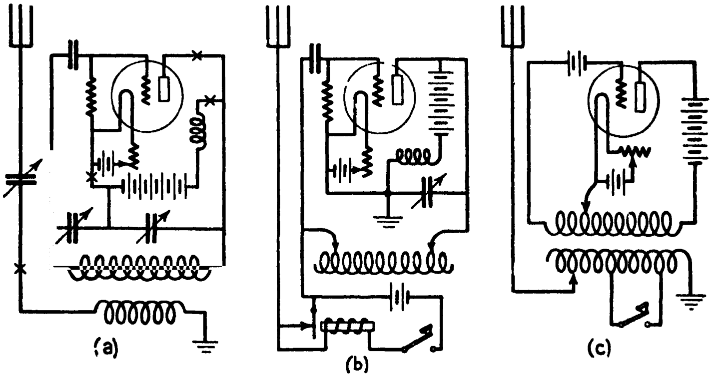


Fig. 519 — Popular Telegraph Transmitters.

In high-power commercial telegraph transmitters where it would be impracticable to open either the antenna or oscillator circuits on account of the large currents and high voltages used, another system of forming the dots and dashes is employed. In this system, shown in (*c*) of Fig. 519, depression of the key short-circuits a portion of the antenna inductance. By this action the antenna emits oscillations of one frequency when the key is open, and oscillations of another frequency when closed. Of course, for correct reception, care must be exercised to tune to the proper wave. Such a telegraph transmitter is said to be a compensated continuous wave (C.C.W.) transmitter.

409. The Vacuum-Tube Telephone Transmitter. — A radio telegraph transmitter may be converted into a telephone trans-

mitter by substituting a sound modulating system for the telegraph key. By a modulating system or *modulator* is meant a device for moulding the generated wave to conform to an envelope which has the characteristics of the sound to be transmitted Since sounds are waves ranging in frequency from about 16 to 10,000 cycles per second, modulation may be considered as being a superposition of such audio-frequency waves on the radio waves generated by the oscillator. This is somewhat analogous to the superposition

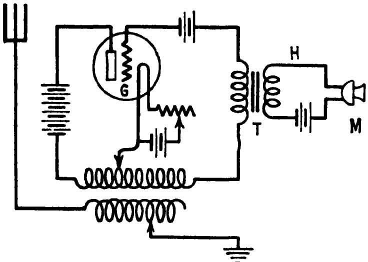


Fig. 520. — Radio Telephone Transmitter Using Grid Modulation.

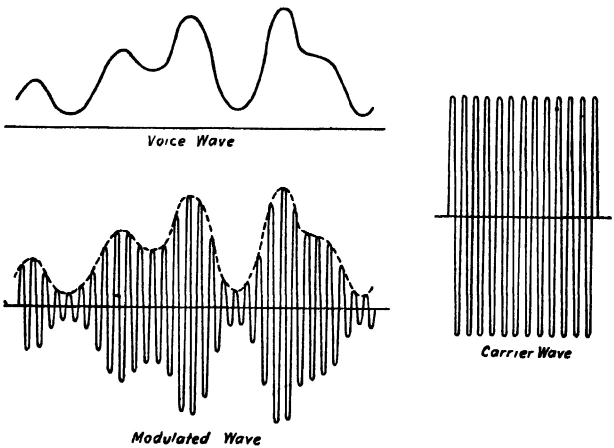


Fig. 521. — Modulating High-frequency Currents for Radio Telephony.

Top Audio-frequency wave of voice current
Right High-frequency or carrier wave
Bottom· Modulated wave formed by superposing the voice current on the carrier wave

of the speech waves on the direct current used in the ordinary wire telephone.

Modulation may be accomplished by inserting a microphone and transformer in the grid circuit of the vacuum-tube oscillator, as shown in Fig. 520. This arrangement, known as *grid modulation*, is very simple and effective in low-power circuits. The sound waves impingeing upon the microphone M are converted into corresponding electrical current waves in the local circuit H, and by means of transformer T suitably varying potentials are impressed upon the grid G. Thus the grid is subjected to two sets of voltage variations, one being the very rapid radio-frequency oscillations and the other being the relatively slow voice or sound frequency variations. As a result the oscillations generated by the tube, which are constant in frequency, are varied in amplitude in accordance with the sound wave so that a curve passing through the successive maxima of the radio-frequency waves represents the sound wave. Fig. 521 shows the individual waves and their combined resultant. The sound wave is often termed the *voice wave*, while the radio-frequency oscillations are frequently termed the *carrier wave*.

410. The Heising System of Modulation. — Since grid modulation in radio telephony is practical only for small transmitters, other means must be devised for modulation in medium and high power systems. The Heising method, illustrated in Fig. 522, is perhaps the most common for this purpose. The system employs two tubes of the same capacity, 1 is the oscillator and 2 is the modulator.

The secondary winding of the modulation transformer T is connected in the grid circuit of the modulator tube. The audio-frequency choke coil AC keeps the total current supplied by battery B to the plates of both tubes practically constant. The radio-frequency currents developed by the oscillator tube are carried from the plate of that tube through wire w directly to the oscillating circuit; the radio-frequency choke RC prevents the high-frequency oscillations from entering the modulator tube circuit.

If the oscillator tube is operating alone, the energy supplied by battery B to the oscillator is constant, and the high-frequency current supplied to the antenna will be constant. If, now, a sound is directed into the microphone M, the grid of the modu-

lator tube will undergo voltage fluctuations, which in turn will cause the plate current of that tube to vary. Since the choke AC will only permit the current from B to change slightly, there will be variations in the plate current of the oscillator in view of the fact that the available energy from battery B, divided between the two tubes, is practically constant. At an instant when the plate current of the modulator increases, the input to the oscillator from B is momentarily reduced; as a result the energy of the transmitted wave is reduced, that is, the amplitude

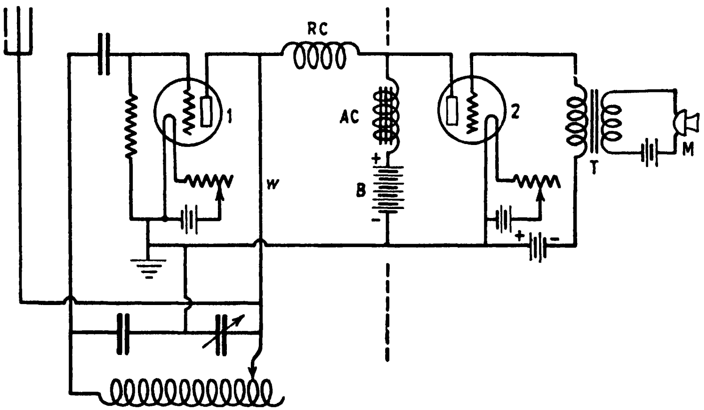


Fig. 522. — Radio Telephone Transmitter Using Heising System of Modulation.

Antenna and oscillator at left of dotted line; modulator and microphone at right. The current output of the B-battery is practically constant.

of the radio waves is reduced. Thus, modulation is effected by causing one tube to absorb energy from a source of fixed output supplying the oscillator tube.

411. Frequency Control of Oscillators. — The oscillator tubes of radio telephone and telegraph transmitters often vary the frequency (or wave length) of their oscillations on account of variation of the constants of their circuits with changes of load. Since such wave length variations make reception difficult, and may lead to interference with other transmitters, a close supervision of frequency is necessary. Until recently such supervision could be accomplished only by a high-grade wavemeter.

This device, shown in Fig. 523, usually consists of a fixed inductance L, a variable condenser C, a resonance indicator, and a suitable shield S. The resonance indicator depicted is a heater element H and thermocouple T (see ¶ 246), together with a galvanometer G. The deflection of the instrument will be proportional to the square of the alternating current through the heater element of the couple.

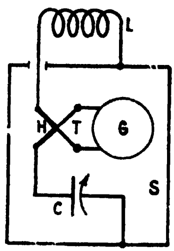


Fig. 523. — Wavemeter Circuit.

In using a wavemeter to measure the wave length of a transmitter, the wavemeter is brought near the oscillator and the condenser capacitance is varied carefully until a maximum deflection is shown on the galvanometer. For this setting of the condenser the wave length may be determined by reference to the calibration curve of the instrument. The wavemeter should never be brought closer to the oscillator than is necessary to obtain a reasonable galvanometer deflection.

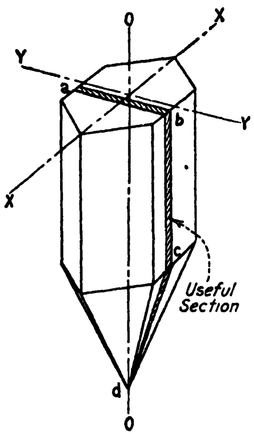


Fig. 524. — Quartz Crystal Showing Section Useful in the Production of Electrical Oscillations.

Although the frequency control of transmitters by means of wavemeters is electrically satisfactory, its effectiveness is limited by the watchfulness of the station attendant. Attempts to reduce the care required for the adjustment of frequency resulted in the development of the piezoelectric oscillator, ¶ 387. This device consists of a carefully ground section of quartz crystal clamped between two mutually insulated metal plates. The quartz used must be carefully selected to be free from bubbles or cracks, and must not be a so-called "twin crystal" as such crystals are useless for the purpose. The section to be used is cut from the crystal in the manner shown in Fig. 524, wherein the desired section is indicated by abcd. This section has its flat sides parallel to the OO and

YY axes, the former being the optical axis of the crystal, and the latter being an axis perpendicular to any two opposite and parallel sides of the crystal. The third or thickness dimension of the section is then parallel to the XX or "electrical axis," which axis passes through an edge of the crystal perpendicular to the YY axis.

When the above-described section of quartz is mounted between two metal plates and pressure is exerted upon them, an alternating potential is found to exist between the plates. The frequency of this E. M. F. is inversely proportional to the thickness of the crystal, its value being about 3,000,000 cycles per

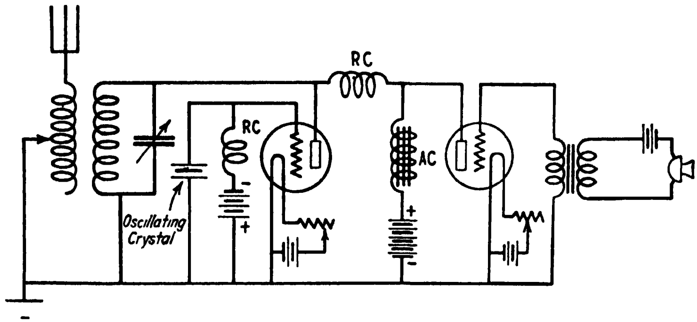


Fig. 525 — Crystal-controlled Radio Telephone Transmitter.
RC and AC are radio- and audio-frequency chokes respectively

second for a thickness of 1 millimeter. By connecting the two clamping plates to the grid circuit of a vacuum tube, the tube will oscillate at the frequency of the crystal, regardless of the electrical constants of its circuit. Thus the oscillator tube is really an amplifier of the oscillations generated by the crystal. By careful grinding, a crystal may be constructed for an oscillator to maintain an absolutely constant wave length at any desired value. Fig. 525 shows a simple crystal-controlled oscillator used for radio telephony.

412. How the Waves Leave the Transmitting Antenna. — Consider a *vertical* aerial (lead-in wire only), as in Fig. 509, and assume that at a certain instant the top of the aerial is negatively charged, while the counterpoise, or ground, is positively charged. A static strain is formed, as shown in Fig. 526,

by the E. M. F. impressed upon the antenna. When the antenna E. M. F. reverses, the counterpoise becomes negatively charged, the aerial becomes positively charged, and the wave immediately falls away from the aerial. The side of the wave next to the antenna is positively charged, and the positive charge at the bottom of the antenna repels the wave into space. There is a repelling action between adjacent wave sides; this is illustrated in Fig. 526, wherein only the electrostatic field is represented for simplicity. In this way the electromagnetic waves, comprising the magnetic and electrostatic fields at right angles with each other, are launched from the transmitting antenna.

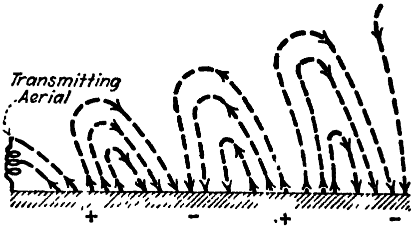


Fig. 526. — Propagation of Electromagnetic Waves from an Antenna.

QUESTIONS

1. What is the fundamental principle of radio signaling?
2. What is the velocity of propagation of electromagnetic waves?
3. How would you ascertain the wave length if the frequency of oscillation is known?
4. What is an oscillatory circuit?
5. A circuit has a capacitance of 0.001 microfarad and an inductance of 0.02 millihenry. What is its natural frequency and wave length?
6. How are electromagnetic waves produced?
7. What is the difference between damped waves and continuous waves?
8. Describe a few forms of counterpoise.
9. What is meant by the directional effect of an antenna?
10. How is the wave length of an antenna determined?
11. What is meant by damping and upon what factors does damping depend?
12. What methods are employed for exciting the antenna circuit in transmission systems?
13. Describe how circuits are coupled.
14. What is the advantage of quenching the spark?
15. What is the principle of an arc transmission system?
16. What is the fundamental principle upon which a vacuum tube operates?

17. How can a vacuum tube serve as an oscillation generator?

18. What is meant by modulation?

19. Outline the differences between the grid and Heising systems of modulation.

20. How may a quartz crystal be used to regulate the frequency of radio oscillators?

21. How do radio waves leave the antenna?

22. What conditions must be met in order that a vacuum tube may generate high-frequency oscillations?

LESSON XXXIV

RADIO RECEPTION

Radio Receiving Sets — Radio Detectors — Vacuum-Tube Receivers — Regenerative Receivers — Radio-Frequency and Audio-Frequency Amplification — The Neutrodyne Receiver — The Super-Heterodyne Receiver — Ear Telephones and Loud Speakers — Loop Reception — Radio Direction Finder — Questions.

413. Radio Receiving Sets. — The preceding lesson was devoted to the production and transmission of electromagnetic waves which were modulated in accordance with the dots and dashes of a telegraph code or with the sounds impressed upon a telephone transmitter. In the former the radiation from the antenna consists of either wave trains of decadent oscillations from spark sets, or of continuous waves from alternators, arcs and vacuum tubes interrupted by means of a buzzer at some audible frequency. In radio telephony the oscillations must be continuous and are varied in amplitude to conform to the sounds transmitted by means of an appropriate modulating system. The reception of these forms of electromagnetic waves and their conversion into telegraph signals or sound waves is the subject of this lesson.

The function of the radio receiving set is to absorb as much energy as possible from the electromagnetic waves available in its vicinity which are emitted from a selected transmitting station, to transform these weak high-frequency oscillations into amplified currents of lower and audible frequency, and to convert these currents into sounds having minimum distortion and sufficient volume. The electromagnetic waves are collected by the antenna system which includes a detector, usually a mineral crystal or a vacuum tube, ¶ 384.

The aerial of a receiving set should be designed to suit the wave or band of waves to be received, and also to fit the receiving set to which it is connected. It ranges from the lofty and lengthy aerial of a long-wave ship or land station to the short

single-wire aerial of a low-wave station. Ordinarily the amateur and broadcasting wave lengths may be received very well with a single-wire aerial from 40 to 80 feet in length, either all vertical or bent into an inverted L. Such an aerial, when connected to the ground, has a fundamental wave length of approximately four and a half times its total length. In situations where ground connections are impossible, as with airplanes, or poor, as in sandy locations, the ground connection of the antenna is replaced by a counterpoise, ¶ 404. In such cases the fundamental wave length of the antenna cannot be expressed in a simple manner.

The aerial of an antenna is usually placed near the ground in order to establish an electrostatic connection with the earth.

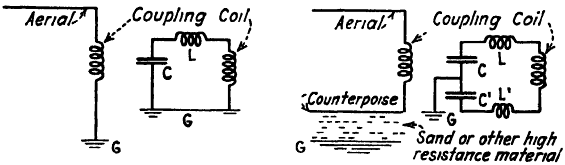


Fig. 527. — Resolution of Antennas into Equivalent Closed Circuits.

Fig. 527 shows how antennas using grounds or counterpoises may be reduced into equivalent simple alternating-current circuits having inductance and capacitance. Resistance of the circuits has been neglected for the sake of simplicity. The condenser C represents the distributed capacitance of the aerial with respect to ground G, and L represents the distributed inductance of the aerial; C′ and L′ represent the corresponding electrical constants for the counterpoise. These equivalent circuits may then be computed by the methods described in Lesson XXVIII.

414. Radio Detectors. — The method employed for detecting the *damped* incoming waves constituting a telegraph message is to *rectify* the feeble currents produced by the incoming high-frequency waves, so that the current shall flow only in one direction through the telephone receivers. By the aid of a small condenser, the equivalent of a unidirectional current pulse is obtained for actuating the telephone receivers

during one wave train. It should be borne in mind that a number of damped wave trains constitute each dot or dash signal. Consequently, for each incoming signal, the telephone receivers will respond to several pulsations of an audio frequency. This rectification of the oscillating antenna current is conveniently accomplished by means of *crystal detectors*, a simple type of which is the silicon detector. This device consists of a piece of fused silicon, set into a cup of metal by means of some alloy of low melting temperature, together with a metal wire resting under slight pressure on the crystal. Such a detector has the property of *unilateral conductivity* and consequently the high-frequency currents will flow through the detector in but one direction.

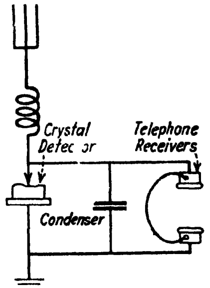


Fig. 528. — Crystal Detector Receiving Set.

The simple circuit in Fig. 528 illustrates the method. The receiving antenna contains both inductance and capacitance, and, therefore, will respond to incoming waves having a frequency equal to its own natural frequency. When damped wave trains impinge upon the antenna, the detector will permit the pulses of electricity to pass through it in one direction only. By inserting a small condenser in parallel with the telephone receiver, charges will be received upon it when the detector prevents the passage of electricity through the detector, the condenser discharging an instant later through the telephone receivers. This causes a pulsating flow of electricity through the telephones at audio frequencies, one pulse for each wave train.

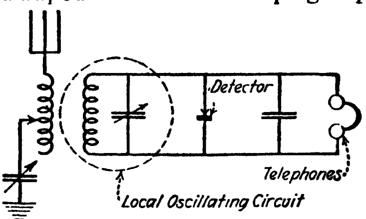


Fig. 529. — Loose-coupled Receiving Set with Crystal Detector.

Fig. 529 shows the connections of a form of loose-coupled receiving set. The arrows indicate that the condensers are adjustable, so as to vary the capacitance.

In detecting the *continuous* incoming waves of a telegraph

message, the crystal detector must be supplemented by a device for rendering the signal intelligible. The reason for this is that a train of continuous waves (i.e. having constant amplitude) representing a dot or dash signal would, when rectified, cause the diaphragm to be attracted and released just once; thereby yielding sounds in the telephone receivers somewhat similar to that emitted by a telegraph sounder in wire telegraphy but decidedly weaker. However, in radio practice, such sounds would easily be rendered unintelligible by atmospheric discharges (so-called static) or other interfering signals. Therefore, a buzzer or other interrupting device must be inserted in the receiver just as it was inserted in the I.C.W. transmitter of ¶ 408. It should be clear that this buzzer, or so-called *tikker*,

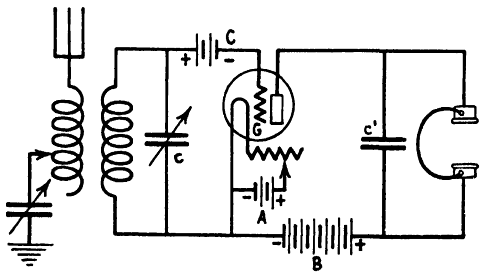


Fig. 530. — Simple Vacuum Tube Receiver.

is necessary either in the continuous wave transmitter or in the radio telegraph receiving set, but not in both. However, neither is required when oscillating vacuum-tube receivers are used.

415. Vacuum-Tube Receivers. — Although crystals are quite satisfactory in the detection of radio signals, their proper setting is disturbed by mechanical shocks and their contacts may be burned out by strong signals. In consequence, the vacuum tube has largely supplanted the crystal detector. While the crystal is considered by many to be as sensitive as a simple vacuum-tube detector, yet, with a slight change of circuit, a vacuum tube may be converted into a *regenerative detector*, ¶ 416, which is far more sensitive than any crystal.

Fig. 530 shows the circuit of a simple vacuum-tube detector used in a receiver. The voltage variations across the condenser

c are impressed upon the grid G of the tube through the C battery. The voltage of this battery is adjusted to select the point on the characteristic curve of the tube for proper operation. Variations of grid voltage produce current variations in the plate circuit comprising the telephone receivers and condenser c′, as explained in ¶ 386. Condenser c′ by-passes the high-frequency fluctuations of the plate current and the telephones receive the rectified current.

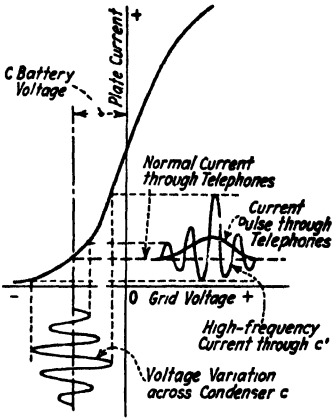


Fig. 531. — Action of a Simple Vacuum-tube Detector Using a Grid Battery.

The plate-current grid-voltage characteristic of the vacuum tube is illustrated in Fig. 531, showing the extent to which rectification is carried out. The greatest rectification will result when the voltage of the C battery conforms to the bend of the characteristic curve. No rectification would be produced at the straight portion of the curve because equal positive and negative swings of the grid voltage yield equal increases and decreases of plate current.

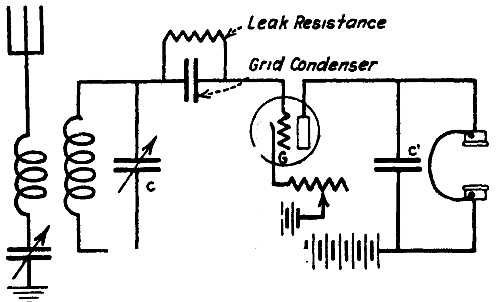


Fig. 532. — Simple Vacuum-tube Receiver Using Grid Leak and Condenser.

Another simple vacuum-tube detector is shown in Fig. 532 In this circuit the C battery is replaced by a grid condenser and a leak resistance, in order to eliminate the voltage adjustment of the battery and to permit the operation of the detector on the straight-line portion of the characteristic. The grid leak and condenser accomplish this object as follows: As a positive voltage is impressed by incoming oscillations upon the grid G, the grid receives electrons from the filament of the tube. If no leak resistance were present, the electrons taken up by the grid when positive, would remain trapped on the grid. This accumulated negative charge would be augmented by the negative voltage of the next half cycle. Thus the grid becomes more strongly negative than would be the case were the grid condenser short-circuited. On the subsequent half cycle, the positive grid voltage would add more captive electrons to the grid. Accordingly, variations of grid potential would cause the plate current to behave as shown in Fig. 533. The high resistance leak across the condenser is necessary for the removal of the captive charges from the grid at the proper rate. If too high a resistance is used, the grid may become so negative as to stop the plate current entirely; on the other hand, if the resistance approaches a short-circuit, the effect of the condenser as a substitute for the C-battery is lost. Usual values of grid condenser capacitance and leak resistance for receiving tubes are respectively 0.00025 microfarad and 2,000,000 ohms.

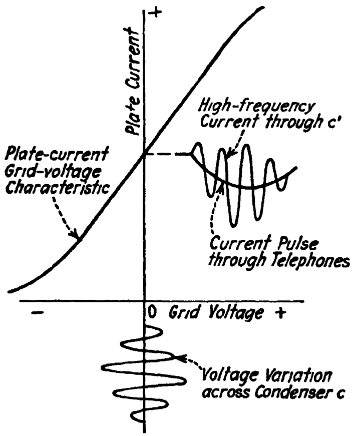


Fig 533. — Action of Vacuum-tube Detector Using Grid Leak and Condenser.

416. Regenerative Receivers. — As was pointed out in ¶ 415, it is quite an easy matter to improve upon the simple tube detector by means of regeneration. Fig. 534 shows a typi-

cal circuit employing this principle. Some of the energy of the plate circuit is returned to the grid by way of the *tickler coil* T and the secondary S of the coupler. This energy combines with that of the incoming signals to produce a strong response in the telephones. The action of T on S, i.e., the *feed-back* from the plate to the grid, must be regulated carefully. for if too much energy is fed back to the grid, the tube will become an oscillator and produce a radio-frequency wave of its own. This wave will combine, or *heterodyne*, with the received wave with the result that a *beat note* of frequency equal to the difference between the

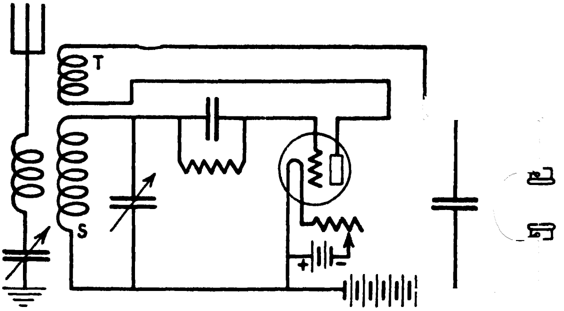


Fig. 534. — Regenerative Receiver.

Energy from plate circuit is fed back to grid circuit of the tube.

one locally generated and the one received, will be heard as a howl in the telephones.

If the receiving tube is carefully manipulated to make the frequency generated exactly the same as the one received, then the maximum signal strength will be obtained. Such operation is known as *synchronous heterodyne reception*, and is adapted for receiving any modulated wave.

For the reception of continuous wave (CW) telegraph signals the frequency of the wave generated by the tube is purposely made slightly different from that of the incoming wave. When the transmitter is operating, the receiver will heterodyne with the incoming wave and produce a beat note in the telephones. When the transmitter stops sending, no sound will be heard in the telephones, because the radio-frequency oscillations still being generated by the receiver are inaudible.

417. Radio-Frequency and Audio-Frequency Amplification. — In order that a vacuum tube detector may operate to the best advantage, it is necessary that the voltages impressed upon its grid be reasonably large. Since the energy ordinarily received in antennas is insufficient to develop such voltages, it is almost always desirable to build up the received radio-frequency impulses before applying them to the detector. The process of building up these radio-frequency currents is termed *radio-frequency amplification.* A simple circuit involving such amplification is shown in Fig. 535. Herein the tube marked 1 is the radio-frequency amplifier; it is connected by means of a coupler M to the antenna, and by means of a radio-frequency trans-

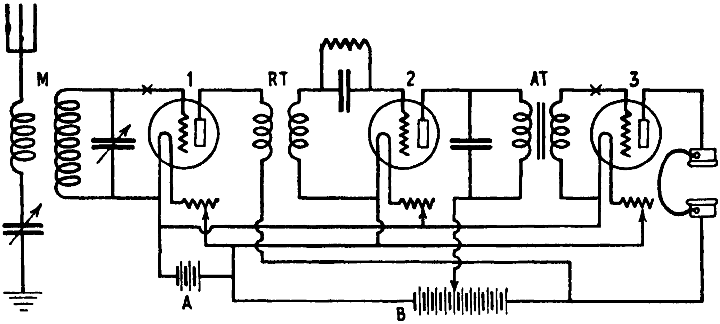


Fig. 535. — Vacuum-tube Receiver Using Radio- and Audio-frequency Amplification.

former RT to the detector tube marked 2. The transformer RT has an air core and resembles a coupler. Additional amplifying tubes may be introduced similarly ahead of the detector. The detector tube converts the radio-frequency oscillations into waves of audible frequencies and passes them to the telephones.

With one or more stages of radio-frequency amplification applied ahead of the detector tube of a receiver, the output may still be too weak to actuate the sound reproducing devices. The output may be increased by means of audio-frequency amplifiers to any suitable value. Tube 3 in Fig. 535 is an audio-frequency amplifier, and is connected to the detector through the audio-frequency transformer AT. Usually two stages of audio-frequency amplification are utilized. Often the second

of the two stages employs a tube of larger capacity, a so-called power tube, in order to yield large volumes of sound in the loud speaker. Audio-frequency transformers are always wound on iron or ferrous cores.

In order to conserve the B battery as well as to improve the quality of reception, C batteries are inserted in amplifier circuits at points marked x in Fig. 535; the negative terminal of the battery is always connected to the grid. Tube number 2 may be made regenerative, but this is inadvisable because such operation will start tube number 1 oscillating unless special precautions are adopted.

418. The Neutrodyne Receiver. — If in a radio-frequency amplifier, transformers are used having a ratio of turns greater than 1 to 1.5, the plate and grid circuits approach resonance. Under these conditions all that is necessary to set the tubes into oscillation is a coupling between the grid and plate. The capacitance between the grid and plate of the tube itself constitutes such coupling. Since oscillation in a multi-tube set invariably results in setting up a beat note or howl, great care is taken to avoid it. Oscillation may be damped out by loading the circuit, or it may be prevented by neutralizing the disturbing internal capacitance of the tubes. The latter method, manifestly superior to the former, was introduced by Hazeltine and incorporated in his "Neutrodyne" receiver.

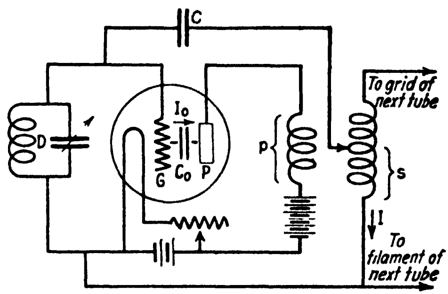


Fig. 536. — Neutralization of Tube Capacitance.

Neutralization of vacuum tube capacitance will be explained by reference to Fig. 536. Herein C_0 represents the capacitance between the grid and the plate of the tube, p and s are two very closely coupled air-core coils having N_p and N_s turns respectively, D is an input tuned circuit, and C is the neutralizing condenser. Coil s is part of the secondary of a radio-frequency transformer.

If an alternating current I_0 is transferred from G to P by means of the tube capacitance C_0, the magnetization set up in p is I_0N_p ampere-turns. The resulting alternating current I in s will set up IN_s ampere-turns, the value of N_s being so adjusted that

$$IN_s = I_0N_p,$$

or

$$\frac{I_0}{I} = \frac{N_s}{N_p}.$$

On the assumption that no leakage nor losses take place in p and s, the resistance and reactance drops in coils p and s will be zero. It follows then, that the alternating voltages across C and C_0 are equal, the batteries having no effect on these voltages. Consequently by ¶ 343, the voltage is

$$\frac{I_0}{2\pi fC_0} = \frac{I}{2\pi fC},$$

or

$$\frac{I_0}{I} = \frac{C_0}{C}.$$

Combining with the previous equation for this current ratio, there results

$$\frac{C_0}{C} = \frac{N_s}{N_p} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \textbf{(165)}.$$

On the basis of this equation the transformers for a neutrodyne receiver are wound to suit any type of tube and any value of C.

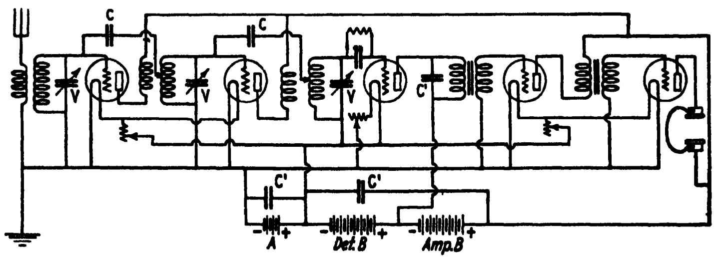


Fig. 537. — Five-tube Neutrodyne Circuit.

Since feed-back is possible from one radio-frequency stage to the next by means of the mutual coupling of two transformers, care should be taken to reduce such coupling to a minimum.

This may be accomplished by placing the axes of the transformers mutually perpendicular to each other. Another method, due to Hazeltine, requires that coils mounted with their axes in a vertical plane shall have these axes inclined at an angle of about 55 degrees with the horizontal.

By neutralizing the internal capacitance of vacuum tubes, the Neutrodyne circuit permits the use of high-ratio radio-frequency transformers and the introduction of any number of stages. These features have made the circuit one of the most useful in radio practice today. Fig. 537 gives the complete circuit of the usual 5-tube receiver of this type. The tuning of the successive grid circuits of the radio-frequency tubes by means of the three variable condensers V renders the receiver highly selective. The condensers C and C′ are respectively neutralizing and by-pass condensers.

419. The Super-Heterodyne Receiver. — The super-heterodyne receiver is the outgrowth of a general recognition of the ineffectiveness of vacuum-tube radio-frequency amplifiers at very high frequencies or low wave lengths. This limitation becomes especially pronounced at wave lengths below 200 meters since the capacitance between grid and filament and between plate and filament of receiving tubes offers paths of low impedance between these elements at such wave lengths. The low impedance causes a current to flow between the tube elements just as in the case of a large condenser at ordinary frequencies. As a result, the high-frequency voltage applied to the grid of a tube is partially short circuited, thereby reducing greatly the effectiveness of the tube. The super-heterodyne system of radio-frequency amplification introduced by Armstrong overcomes this disadvantage.

If a wave of frequency f_1 is combined with another wave of frequency f_2 and passed through a detector, two new waves are produced: — one having a frequency of $(f_1 - f_2)$ and the other of $(f_1 + t_2)$ cycles per second. If f_1 and f_2 are high radio frequencies, the wave of frequency $(f_1 + f_2)$ will be entirely ineffective in the amplifiers. Therefore, the practical result of the combination is just one wave of frequency $(f_1 - f_2)$. This wave may be adjusted to have a low radio frequency, which wave may be amplified with ease. For example, if a 100 meter

wave, having 3,000,000 cycles per second, is to be amplified, a wave of say 2,950,000 cycles per second is combined with it. The combination through the detector results in a wave of 50,000 cycles per second. The output of this or first detector is passed through a series of radio-frequency amplifier stages, called *intermediate-frequency* amplifiers.

The intermediate amplifiers are rather broadly tuned so as not to impair the quality of the sound. After passing through these amplifiers, the intermediate radio-frequency wave is applied to a second detector tube which separates from it the

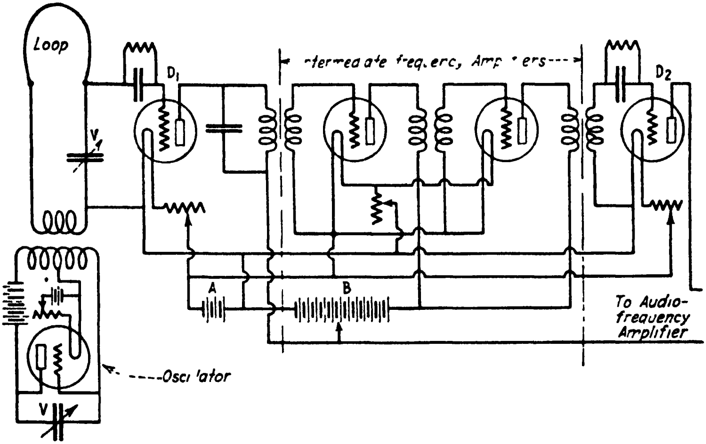


Fig. 538. — Simple Super-heterodyne Circuit.
Two detectors (D_1 and D_2) and two stages of intermediate radio-frequency amplifiers are depicted

sound (or audio) frequencies. Should the volume resulting still be too low, two stages of audio-frequency amplification may be introduced in the usual manner.

The super-heterodyne circuit is noted for its enormous amplification and unusual selectivity. The reason for the latter will be clear from a numerical example. Suppose that a second wave of 3,005,000 cycles were interfering with the one of 3,000,000 cycles mentioned above. When the 2,950,000 cycle wave generated in the receiver beats with the 3,005,000 cycle wave, the resulting intermediate wave will have a frequency of

55,000 cycles per second. This wave is displaced from the 50,000 cycle or resonant frequency by 10 per cent, whereas the original waves differed by only one-sixth of one per cent. The selective feature, together with the convenience of a loop antenna (¶ 421) common to such a set, makes this type of receiver one of the best available. Fig. 538 shows the usual super-heterodyne circuit. Tuning is accomplished by the variable condensers marked V; the intermediate-frequency circuits are tuned in completed sets to some definite frequency.

Although the super-heterodyne circuit just described is very satisfactory as a receiver, it is nevertheless rather expensive because of the number of tubes involved. For this reason the

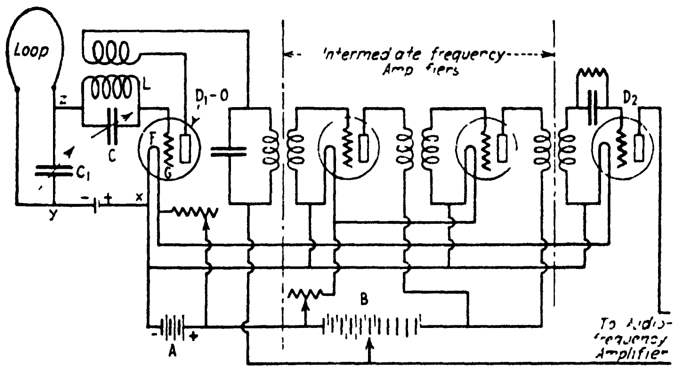


Fig. 539. — Second Harmonic Super-heterodyne Circuit.

second harmonic super-heterodyne shown in Fig. 539 finds great favor. Herein the oscillator is incorporated with the first detector D_1. The tuned circuit LC, which determines the frequency of the oscillator action of the tube D_1-O, is designed to have a natural frequency about half that desired for beating with the signal wave. The second harmonic of this natural frequency is then utilized to produce the intermediate frequency. For example, if the set is tuned for an intermediate radio-frequency of 50,000 cycles, then the circuit LC will be tuned for a frequency of $\frac{1}{2} \times 2{,}950{,}000$ or 1,475,000 cycles when it is desired to receive a 3,000,000 cycle signal wave.

The reason for this procedure will be made clear when circuit

GFxyz in Fig. 539 is considered. There are three condensers in this circuit, marked C, C_1 and FG, the latter representing the small capacitance between the tube elements. Condenser C_1 is bridged by the other two condensers connected in series. If the variable condenser C has a large value, small changes in its capacitance will not appreciably alter the total capacitance of the loop circuit. Consequently it is desirable to make C large by having the tuned circuit LC responsive to lower frequencies, utilizing the second harmonic for heterodyne action.

Other tubes are dispensed with in this super-heterodyne circuit by using one or two intermediate-frequency amplifier tubes for audio-frequency amplification as well; this arrangement is termed *reflex* operation of tubes.

420. Ear Telephones and Loud Speakers. — The sound reproducer of a receiving set is almost exclusively of the electromagnetic type, similar in principle to the customary telephone

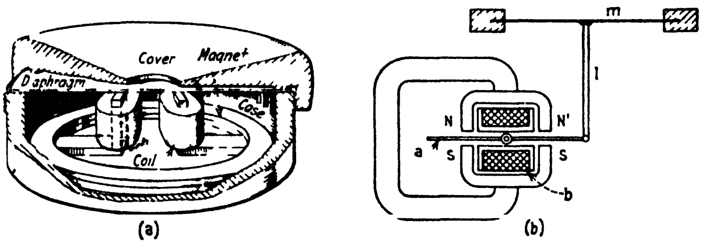


Fig. 540. — Simple and Balanced-armature Watchcase Telephones.

receiver. The human ear cannot detect sounds having frequencies greater than 40,000 cycles per second, and very few persons can detect sounds exceeding 25,000 cycles per second. Sounds of high pitch are usually very weak and for detection demand quiet and close attention. The inertia of the diaphragm of a telephone receiver prevents it from responding readily to currents of more than 10,000 cycles, and the inductance of the electromagnet in the receiver at these or higher frequencies prevents sufficient current flow to operate it satisfactorily even if the diaphragm did respond.

The ear telephone used in radio reception is of the "watch-case" type. It differs from the instrument used in wire teleph-

ony only in the shape of the permanent magnet and the resistance of the windings. The magnet is formed of circular rings with the poles diametrically opposite each other; the resistance is usually about 2,000 ohms per pair of telephones. Two forms of watchcase radio telephones are shown in Fig. 540 at (a) and (b); the first will be called a simple receiver and the latter is known as the balanced-armature type. In the latter the iron vibrating armature, a, is normally balanced between the four poles N, S, and N′, S′. When a current pulse passes through the coil b, the armature becomes polarized, say with a north pole at the left and a south at the right end, giving rise to a torque tending to turn the armature in a counter-clockwise direction. Thus the diaphragm m is deflected by means of the connecting link l, and a sound is produced.

The balanced-armature telephone is much more faithful, in general, than the simple bipolar device shown at (a) in the figure. This is especially true at high volumes of sound. For this reason the device is gaining popularity in the field of loud speakers. Loud speakers have been produced by using the simple bipolar telephone with a horn; the reproducing unit having a large clearance between the diaphragm and pole-pieces, and the resistance of the coils being about 2,000 ohms. Such loud speakers are limited in volume and tone quality, the limitations being imposed by both reproducing unit and horn. In the balanced-armature telephone, tone quality and volume are improved but the limitation of the horn still remains.

The limitation of the horn is due to the natural frequency of the horn structure, and to the absorption of low notes; both effects causing distortion of the reproduced sound. These limitations together with the recognized directional qualities of the horn have been overcome in the cone-type loud speaker. In this device a balanced-armature unit operates a paper cone having practically no fundamental frequency. A properly constructed cone speaker gives very satisfactory results because practically the full range of sound frequencies are reproduced faithfully.

421. Loop Reception. — When two aerials are in the plane of a wave, so that the wave strikes one before the other, then, at a certain instant, the E. M. F.'s generated in the aerials will be in

the same direction, but will have different magnitudes, so long as the aerials are spaced less than one-half wave length apart. If these aerials are connected together at their tops with a wire, and at their bottoms with another wire, so as to form a *loop*, there will be two E. M. F.'s tending to neutralize each other, but since one has a greater magnitude than the other, the *resultant* E. M. F., equal to their difference, will produce a current in the loop.

At any instant, the potentials of the waves in a certain locality may be represented by the sine curve, as in Fig. 541, in which the wave is assumed to move from left to right. AB and CD are two vertical wires connected at their tops and bottoms by

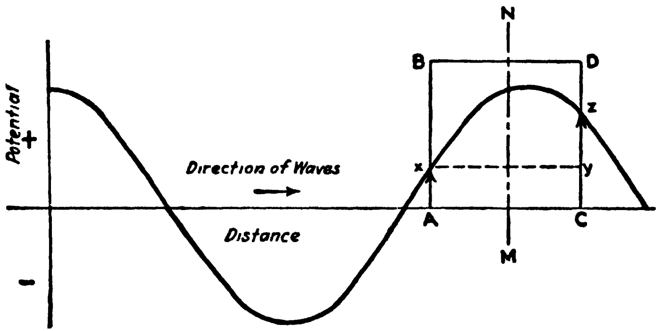


Fig. 541. — Principle of Loop Reception.

similar wires, so as to form a loop, pivoted about MN. At a given instant, when the loop is turned so as to be in the plane of the wave as the latter is passing across the surface of the earth, there is an E. M. F. induced in AB, the magnitude of which may be represented by Ax (the height of the wave at that point) and, say, in an upward direction. At the same instant, there is an E. M. F. induced in CD, the magnitude of which may be represented by Cz, and also in an upward direction. These two E. M. F.'s are opposing each other in the loop, but Cz is greater than Ax by an amount equal to their difference, or yz; therefore, there will be present a resultant E. M. F., yz, which produces a current in the loop. This principle is utilized in loops used with receiving sets and in radio direction finders.

422. Radio Direction Finder. — The so-called *radio direction finder* makes it possible to determine, with a high degree of accuracy, the direction from which radio waves are being received. Its most important application is in the navigation of vessels and airplanes. Bearings may be taken on distant known stations and, after applying certain corrections for the curvature of the earth, climatic conditions, etc., the location of the direction finder may be determined by triangulation. The simplified apparatus consists of a vertically pivoted loop of wire, say five feet square with twenty turns of light wire, shunted with a variable condenser, and connected to some type of radio receiving apparatus containing an amplifier.

Suppose that the loop, tuned by the condenser, is turned so that its plane is at right angles to the direction of the wave. Then, any point in the wave meets AB and CD of Fig. 541 at the same instant, and equal opposing E. M. F.'s are induced at all times. Their resultant is continually zero, and no current will flow in the loop. Therefore, the amount of energy received by the loop depends upon the angle which the loop makes with the wave, being a maximum when the plane of the loop is parallel to the direction of the wave, and a minimum when the loop is in the quadrature position. Thus, with the loop connected to some detecting device, when the signal fades to zero as the loop is turned, it is known that the signal is coming from a direction which is at right angles to the plane of the loop. When the loop is in this position, a very slight change in the angle between the coil and the direction of wave propagation, makes a great difference in the amount of energy received and, therefore, in the strength of the signals. Consequently, the apparatus is very sensitive when in this position. However, it is quite insensitive when the plane of the loop is pointing towards the transmitting station, as a great change in the angle produces only a small change in the strength of the signals.

In order to obtain increased sensitivity, a second, or *auxiliary loop*, is sometimes pivoted about the same axis with the *main loop* and fixed permanently at right angles to it as in Fig. 542. When the plane of the main loop is parallel to the direction of the wave, it is receiving its maximum amount of energy, and the auxiliary loop is receiving the minimum amount of energy.

Then, when the auxiliary loop is connected in series with the main loop, by means of a reversing switch, no difference in the intensity of a signal should be heard in the telephone receivers when the reversing switch is thrown in either position.

When the main loop is not in line with the radio wave, both loops will receive energy, so that when the reversing switch is thrown in one direction, the energy received by the auxiliary loop will be added to that received by the main loop, thus producing a strong signal. When the reversing switch is thrown in the opposite direction, the resultant E. M. F. in the auxiliary

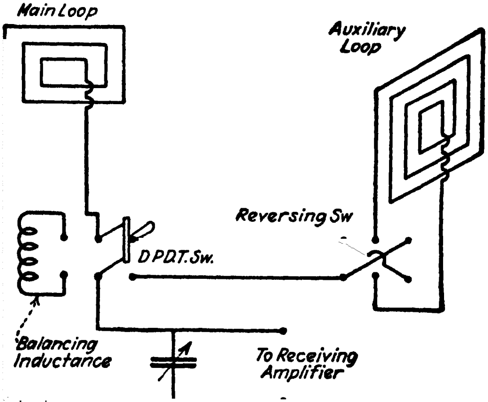


Fig. 542. — Loop Antenna Employing Main and Auxiliary Loops for Increased Sensitiveness.

loop opposes the resultant E. M. F. in the main loop, so that a weaker signal results. The loops can be placed easily and accurately so that no change in the intensity of the signals is noted when the reversing switch is thrown in either position. One of the loops then is in the plane of the wave.

By first using the main loop alone, the transmitting station may be "tuned in" and the approximate direction determined, obtaining accuracy later by switching in the auxiliary loop. Since the energy received is small, it is necessary to use a multi-stage amplifier. With such an apparatus it is possible to obtain an accuracy of one degree when receiving at a distance of several hundred miles from a transmitting station.

QUESTIONS

1. On what general principles do receiving sets operate?
2. Explain the action of a vacuum tube as an amplifier.
3. Describe the principle of loop reception.
4. Explain how a radio direction finder is operated.
5. Explain the principle of radio telephony.
6. Explain the operation of a vacuum-tube detector using a grid condenser and leak.
7. Draw a circuit to show the use of a crystal as a detector.
8. What is the purpose of the tickler coil of a regenerative receiver?
9. Describe the method of synchronous heterodyne reception.
10. Define radio- and audio-frequency amplification.
11. How does the neutrodyne circuit compensate for tube capacitance?
12. Why is radio-frequency amplification carried out at " Intermediate " frequencies in the super-heterodyne?
13. Why are two detectors necessary in the super-heterodyne?
14. Explain the action of the second harmonic super-heterodyne.
15. Describe the balanced-armature type of telephone reproducer.

APPENDIX

Table XXII. Mensuration Rules

Area of triangle	= $\frac{1}{2}$ (base × altitude). $\sqrt{s(s-a)(s-b)(s-c)}$, where a, b and c are the lengths of the sides and $s = \frac{1}{2}(a+b+c)$.
Area of parallelogram	= base × altitude.
Area of trapezoid	= altitude × $\frac{1}{2}$ sum of parallel sides.
Circumference of circle	= diameter × 3.1416.
Diameter of circle	= circumference × 0.3183. 4 × area ÷ circumference.
Area of circle	= diameter squared × 0.7854. radius squared × 3.1416.
Area of ellipse	= product of diameters × 0.7854.
Area of regular polygon	= $\frac{1}{2}$ (sum of sides × apothem).
Lateral surface of cylinder	= circumference of base × altitude.
Volume of cylinder	= area of base × altitude.
Surface of sphere	= diameter × circumference. 12.566× radius squared.
Volume of sphere	= diameter cubed × 0 5236. radius cubed × 4 189.
Surface of pyramid or cone	= $\frac{1}{2}$ (circumference of base × slant height).
Volume of cone	= $\frac{1}{3}$ (area of base × altitude).

Table XXIII. Conversion Table of Lengths

To reduce	Multiply by	To reduce	Multiply by
Miles to kilometers	1.6093	Kilometers to miles	0.62137
" " yards	1760.	" " meters	1000.
" " meters	1609.3	Meters to miles	0.0006214
Yards to meters	0.91440	" " yards	1.0936
" " feet	3.	" " centimeters	100.
Feet to meters	0.30480	" " feet	3.2808
" " inches	12.	Centimeters to millimeters	10.
Inches to mils	1000.	Centimeters to inches	0.39370
" " centimeters	2.5400	Millimeters to inches	0.039370
" " millimeters	25.400		

Table XXIV. Conversion Table of Areas

To reduce	Multiply by	To reduce	Multiply by
Sq. miles to acres	640.	Sq. kilometers to sq. miles	0 3861
Sq. yards to sq. meters	0.83613	Sq. meters to sq. yards	1.1960
Sq. feet to sq. meters	0.09290	" " " sq. feet	10.764
Sq. inches to sq. centimeters	6.4516	Sq. centimeters to sq. inches	0.15500
Sq. inches to circular mils	1,273,238.	" " " circular mils	197,861.

Table XXV. Conversion Table of Volumes

To reduce	Multiply by	To reduce	Multiply by
Cu. yards to cu. meters	0.76456	Cu. meters to cu. yards	1.3080
Cu. feet to cu. meters	0.02832	" " " cu. feet	35.316
" " " liters	28.317	Liters to cu. feet	0.035317
Cu. inches to cu. centimeters	16.387	Cu. centimeters to cu. inches	0.061027
Cu. inches to liters	0.01639	Liters to cu. inches	61.023
Gallons to cu. inches	231.	" " cu. centimeters	1000.
" " liters	3.7854		
Pounds of water to liters	0.4536	Liters to gallons	0.26417

Table XXVI. Conversion Table of Weights

To reduce	Multiply by	To reduce	Multiply by
Tons to kilograms	907.18	Kilograms to tons	0.001102
" " pounds	2000.	" " grams	1000.
Pounds to kilograms	0.45359	" " pounds	2.2046
" " ounces	16.	Grams to milligrams	1000.
Ounces to grams	28.349	" " ounces	0.03527
" " grains	437.5	" " grains	15.432
Grains to grams	0.06480	Grains to Troy ounces	480.

Table XXVII. Conversion Table of Force, Energy, Power, etc.

To reduce	Multiply by	To reduce	Multiply by
Pounds to dynes	444,520.	Dynes to pounds	0.000002249
Ft.-lbs. to kilogram-meters	0.13825	Kilogram-meters to ft.-lbs.	7.233
Ft.-lbs. to ergs	13,549,000.	Ergs to ft.-lbs.	0.0000000738
" " joules	1.3549	Joules to ft.-lbs.	0.7381
" per second to horse power	0.00182	H.P. to ft.-lbs. per second	550.
H.P. to watts	746.	Watts to H.P.	0.001342
B.T.U. to calories	251.8	Calories to B.T.U.	0.003971
Calories to joules	4.1893	Joules to calories	0.2387
Lbs. per sq. foot to kilograms per sq. meter	4.8824	Kilograms per sq. meter to lbs. per sq. foot	0.2048
Lbs. per sq. inch to grams per sq. centimeter	70.307	Grams per sq. centimeter to lbs. per sq. inch	0.01422
Miles per hour to feet per sec.	1.4667	Feet per sec. to miles per hour	0.68182
Miles per hour to centimeters per sec.	44.704	Centimeters per sec. to miles per hour	0.02237

Table XXVIII. Comparative Table of Gages

Giving the respective diameter and area of each number

Gage No.	American Wire Gage (Brown & Sharpe)		Birmingham Wire Gage (Stubs)		Standard Wire Gage (British)	
	Diameter	Area	Diameter	Area	Diameter	Area
	Inches	Circular Mils	Inches	Circular Mils	Inches	Circular Mils
7-0	....	....	.	....	0.500	250000.
6-0	....	....	...	....	0.464	215300.
5-0	....	....	...	....	0.432	186600.
4-0	0.4600	211600.	0.454	206100.	0.400	160000.
3-0	0.4096	167800.	0.425	180600.	0.372	138400.
2-0	0.3648	133100.	0.380	144400.	0.348	121100.
0	0.3249	105500.	0.340	115600.	0.324	105000.
1	0.2893	83690.	0.300	90000.	0.300	90000.
2	0.2576	66370.	0.284	80660.	0.276	76180.
3	0.2294	52630.	0.259	67080.	0.252	63500.
4	0.2043	41740.	0.238	56640.	0.232	53820.
5	0.1819	33100.	0.220	48400.	0.212	44940.
6	0.1620	26250.	0.203	41210.	0.192	36860.
7	0.1443	20820.	0.180	32400.	0.176	30980.
8	0.1285	16510.	0.165	27230.	0.160	25600.
9	0.1144	13090.	0.148	21900.	0.144	20740.
10	0.1019	10380.	0.134	17960.	0.128	16380
11	0.09074	8234.	0.120	14400.	0.116	13460.
12	0.08081	6530.	0.109	11880.	0.104	10820.
13	0.07196	5178.	0.0950	9025.	0.092	8464.
14	0.06408	4107.	0.0830	6889.	0.080	6400.
15	0.05707	3257.	0.0720	5184.	0.072	5184.
16	0.05082	2583.	0.0650	4225.	0.064	4096.
17	0.04526	2048.	0.0580	3364.	0.056	3136.
18	0.04030	1624.	0.0490	2401.	0.048	2304.
19	0.03589	1288.	0.0420	1764.	0.040	1600.
20	0.03196	1022.	0.0350	1225.	0.036	1296.
21	0.02846	810.1	0.0320	1024.	0.032	1024.
22	0.02535	642.4	0.0280	784.	0.028	784.0
23	0.02257	509.5	0.0250	625.	0.024	576.0
24	0.02010	404.0	0.0220	484.	0.022	484.0
25	0.01790	320.4	0.0200	400.	0.020	400.0
26	0.01594	254.1	0.0180	324.	0.018	324.0
27	0.01420	201.5	0.0160	256.	0.0164	269.0
28	0.01264	159.8	0.0140	196.	0.0148	219.0
29	0.01126	126.7	0.0130	169.	0.0136	185.0
30	0.01003	100.5	0.0120	144.	0.0124	153.8
31	0.008928	79.70	0.0100	100.	0.0116	134.6
32	0.007950	63.21	0.0090	81.	0.0108	116.6
33	0.007080	50.13	0.0080	64.	0.0100	100.0
34	0.006305	39.75	0.0070	49.	0.0092	84.64
35	0.005615	31.52	0.0050	25.	0.0084	70.56
36	0.005000	25.00	0.0040	16.	0.0076	67.76
37	0.004453	19.83	...	....	0.0068	46.24
38	0.003965	15.72	...	....	0.0060	36.00
39	0.003531	12.47	...	....	0.0052	27.04
40	0.003145	9.888	...	....	0.0048	23.04

INDEX

[The figures refer to page numbers.]